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CONFIDENTIAL

SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE



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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC



VOLUME 6B

# METHODS OF SUBMARINE BUOYANCY CONTROL



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VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
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WASHINGTON, D. C., 1946

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## *NOTES ON THE ORGANIZATION OF NDRC*

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A — Armor and Ordnance
Division B — Bombs, Fuels, Gases, & Chemical Problems
Division C — Communication and Transportation
Division D — Detection, Controls, and Instruments
Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1 — Ballistic Research
Division 2 — Effects of Impact and Explosion
Division 3 — Rocket Ordnance
Division 4 — Ordnance Accessories
Division 5 — New Missiles
Division 6 — Sub-Surface Warfare
Division 7 — Fire Control
Division 8 — Explosives
Division 9 — Chemistry
Division 10 — Absorbents and Aerosols
Division 11 — Chemical Engineering
Division 12 — Transportation
Division 13 — Electrical Communication
Division 14 — Radar
Division 15 — Radio Coordination
Division 16 — Optics and Camouflage
Division 17 — Physics
Division 18 — War Metallurgy
Division 19 — Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee



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# NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.



The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

Vannevar Bush, Director
*Office of Scientific Research and Development*

J. B. Conant, Chairman
*National Defense Research Committee*

# FOREWORD

Improvement of performance in many operations carried out by Service personnel may be brought about through an understanding of the physical factors involved and by a scientific analysis of the operation. How true this is in the important operation of diving a submarine is illustrated in this report.

This report summarizes an applied research project conducted by the staff of the Woods Hole Oceanographic Institution in such close cooperation with the Navy that it may most accurately be described as a joint Navy-NDRC project. The Division is deeply appreciative of the facilities for experimentation provided by the Navy and for the opportunities given for the observation of operations which were made freely available to the staff of the Institution. In particular, the Division is greatly indebted to Dr. A. C. Redfield of the Woods Hole staff, who undertook the preparation of this report.

Undoubtedly, as the design of submarines is modified and as further studies of oceanographic conditions provide additional data, the operating practices will require modification. This report, however, emphasizes factors of general applicability and discusses methods which may be employed in an even more refined analysis of the operations here discussed.

John T. Tate
Chief, Division 6

# PREFACE

THE PRIMARY aim of this volume is to clarify the problems encountered in diving a submarine. In the early days of submarine operation, the ballast adjustments were made mainly by feel and by accumulated experience. Gradually diving officers came to realize that relatively large changes in the density of the water with depth would sometimes be encountered. Lacking contact with oceanography, however, they did not suppose that such conditions were predictable or could in any way be charted. The possibility of encountering unexpectedly marked density changes made it advisable to be somewhat cautious in diving through a considerable depth range.

Once it was realized that the distribution of temperature and salinity in the sea directly affected submarine diving operations, measurements of the effects and the charting of the available oceanographic data in a form convenient to the diving officer were undertaken. During the war period most of the studies of the performance of submerged submarines and of the compressibility of their hulls had to be carried out during the course of training activities. The precision and completeness of the data presented in this volume, therefore, leave much to be desired. Diving officers have found, however, that even rough measurements and a general understanding of the factors influencing the distribution of density in the sea can be helpful.

A. C. REDFIELD

# CONTENTS

## Chapter 1

# INTRODUCTION

When a submarine is at the surface, its weight is supported in part by the displacement of the main ballast tanks which are filled with air. When it submerges, these tanks are filled with water and no longer have a buoyant effect. It is then essential that the weight of the vessel be very nearly equal to that of the water which it displaces. Only under this condition can its depth be controlled by adjustments of the angles of the diving planes and of the hull.

Fine adjustments in weight are made by changing the quantity of water in the auxiliary or other variable ballast tanks, and when this is satisfactorily accomplished the submarine is said to be *in trim*.

The basic condition for submarine operation is a state of trim at periscope depth. From there it may return to the surface merely by refilling the main ballast tanks with air. This is an "all or none" operation requiring no careful adjustment since relatively large variations in buoyancy are tolerable in the surfaced vessel. So long as it remains submerged, however, trim must be adjusted to the end that the buoyancy forces may be kept within the control of the dynamic forces arising from the diving planes as the vessel moves through the water.

If the submarine changes its depth substantially, an adjustment in trim is required for several reasons. As the depth increases, the pressure due to the overlying water compresses the hull, and since its displacement is decreased, it becomes less buoyant. The increase in pressure with depth also compresses the sea water and thus increases its density. This serves to increase the buoyancy of the submarine. With submarines of present construction the compression of the hull exceeds the compression of sea water and the resultant effect of increasing depth is a decrease in buoyancy.

Since the compression of sea water and the compression of the hull are proportional to the depth, for any particular submarine the adjustment in ballast required to compensate for the change in buoyancy with depth can be allowed for simply, if other conditions affecting buoyancy are constant. Many diving officers have developed rules, based on their experiences, for the amount of ballast to be pumped out on descent. In practice, however, great uncertainty accompanies the use of such rules because the density of the sea water in which the submarine may operate frequently varies with depth.

If the temperature and salinity of sea water were uniform throughout the depth of submergence, these simple rules based on the compression effects would be adequate for trim adjustment. However, when the temperature and salinity of the water change with depth so as to increase substantially the density of the deeper layers, the weight of the water displaced by a descending submarine increases and the vessel becomes more buoyant. If the effects of compression were negligible, water would need to be flooded into the auxiliary tanks until the weight of the vessel equaled the increased weight of the water it displaced.

When the effects of compression and the presence of a density gradient due to temperature or salinity changes are simultaneously considered, the presence of the density gradient will always decrease the amount of ballast water which must be pumped out on account of compression. If the density gradient is sufficiently strong, it will overbalance the effect of compression, and water must be flooded in on descent instead of being pumped out as required by the compression.

Submariners have long been aware that such density gradients exist, for when strongly developed they may retard the descent or ascent of the submarine. Strong gradients of this sort are known in the Service as *density layers*. Frequently, density layers are encountered strong enough to permit the submarine to float supported by the denser medium, or *balance,* without using the planes to control depth. Formerly, this maneuver was discouraged because of the uncertainty of the operation when the hydrography of the water is unknown.

Prior to 1943 submarines were not equipped with instruments to inform the diving officer whether density gradients existed in the water into which he submerged. Adjustments in trim were made entirely by trial. Under these conditions much time is frequently consumed in pumping and flooding ballast before satisfactory control is obtained. In peacetime exercises, when submarines may be controlled at high speed by the use of the diving planes, regardless of exact adjustments of buoyancy, these difficulties were relatively unimportant.

In wartime, the necessity for maneuvering rapidly and silently becomes compelling. When submarines are sent into unfamiliar waters and may need to submerge in the greatest haste, delay in reaching the desired depth results, and the period of noisy operation of the ballast pumps is prolonged. The uncertainty of the operation must add greatly to the mental strain of the men concerned. The magnitude of the uncertainty is reflected in the report of a submarine which, early in the war, was on patrol in Japanese waters:

> "Off Fuji Wan we encountered the heaviest density layer for the cruise. At 160-foot depth it was necessary to flood 7,000 pounds to auxiliary instead of removing 7,000 pounds as is customary—a total of 14,000 pounds difference."

Since it may take as much as one minute to pump 1,000 pounds of ballast water out of the tanks, the delays on encountering such a condition unexpectedly may be very great.

From the foregoing, it is apparent that to bring his vessel into good trim at a desired depth with the greatest speed and precision, the diving officer should know in advance the way in which the buoyancy of the water (density) will vary with depth. This information might be obtained from a suitable instrument lowered from the vessel, but it is more practical to have the instrument carried down by the submarine, since this not only permits information for subsequent use to be secured by an exploratory dive, but also indicates the conditions which are being encountered while a dive is under way.

The submarine *bathythermograph* [BT][a] is an instrument which draws a graphic record of the temperature of the sea water as a function of depth as the submarine descends. The instrument was designed as an aid in predicting sound ranges, but found almost immediate application as an aid to the diving officer, since the density gradients encountered in diving are due very largely to changes in temperature with depth. A more elaborate instrument, the Model CXJC, which measures the temperature and salinity of the sea water and computes their effect on the buoyancy of the submarine is now being perfected.

The following chapter presents an account of the various kinds of density gradients which occur in the sea and a discussion of the conditions which bring them about and the situations in which they are apt to be encountered. The remainder of the volume is devoted to a discussion of the factors which influence the buoyancy of submarines during submergence and the use of bathythermographs in controlling diving operations.

[a] The abbreviation BT is used because of its widespread adoption by Navy and civilian personnel working with bathythermographs. The author points out that this usage is unofficial and does not have his backing. *Bathythermograph* is the acceptable form but BT appears in this volume when used as an adjective.

# Chapter 2

# DENSITY GRADIENTS IN THE SEA

THE GENERAL principles of oceanography and their relation to naval problems is reviewed in Volume 6A, Division 6 of the Summary Technical Report. The conditions which give rise to gradients of temperature and salinity in various parts of the ocean are discussed there in some detail. The relations of temperature and salinity to density are of particular importance to submarines since they determine the buoyancy conditions encountered in diving. These relationships are discussed in greater detail in this chapter.

The true density of sea water, $\rho$, is influenced by its temperature, its salinity, and the pressure under which it exists. The increasing density of sea water which results from compression with depth may be disregarded in connection with the buoyancy of submarines since it is taken into account in estimating the apparent compression of the submarine's hull. The effective density of the sea water may be estimated from its temperature and salinity, assuming it to be under a pressure of one atmosphere, as at the sea's surface. This function of temperature and salinity is represented by $\rho_{ts}$. The term *density* will be used to refer to this function.[a]

A change in density of 0.001 changes the buoyancy of a fleet-type submarine by approximately 5,400 pounds. The effect of a change in temperature on the density of sea water and on the resulting buoyancy of such a submarine varies with the temperature of the water, as shown in Figure 1. A change in salinity of one part per thousand changes the density by 0.00078 and alters the buoyancy of such a submarine by 4,200 pounds. The effects of salinity and temperature are additive. These and other quantitative relations are considered in greater detail in Chapter 4.

The temperature of the sea's surface and its fresh water tributaries range from 28 to 90 F, depending on latitude and season. The salinity may lie anywhere between 0 and 40 parts per thousand. The changes in density which result from such variations in temperature and salinity, and their estimated effects on the buoyancy of a submerged submarine of 2,400 tons displacement are as follows:

| | Limits of variation | Resulting density change | Resulting buoyancy change |
|---|---|---|---|
| Temperature | 28–90 F | 0.0072 | 39,000 pounds |
| Salinity | 0–40 ‰ | 0.0312 | 168,000 pounds |
| Total | | 0.0384 | 207,000 pounds |

Since changes of this magnitude are not likely to be encountered at any one time or place, the figures are of interest only in showing the magnitude of the compensation which a submarine must be designed to make on this account, and in indicating the range of conditions to which density recording devices should be adapted.

Except where wind, tide, and other currents lead to violent mixing, the temperature and salinity of sea

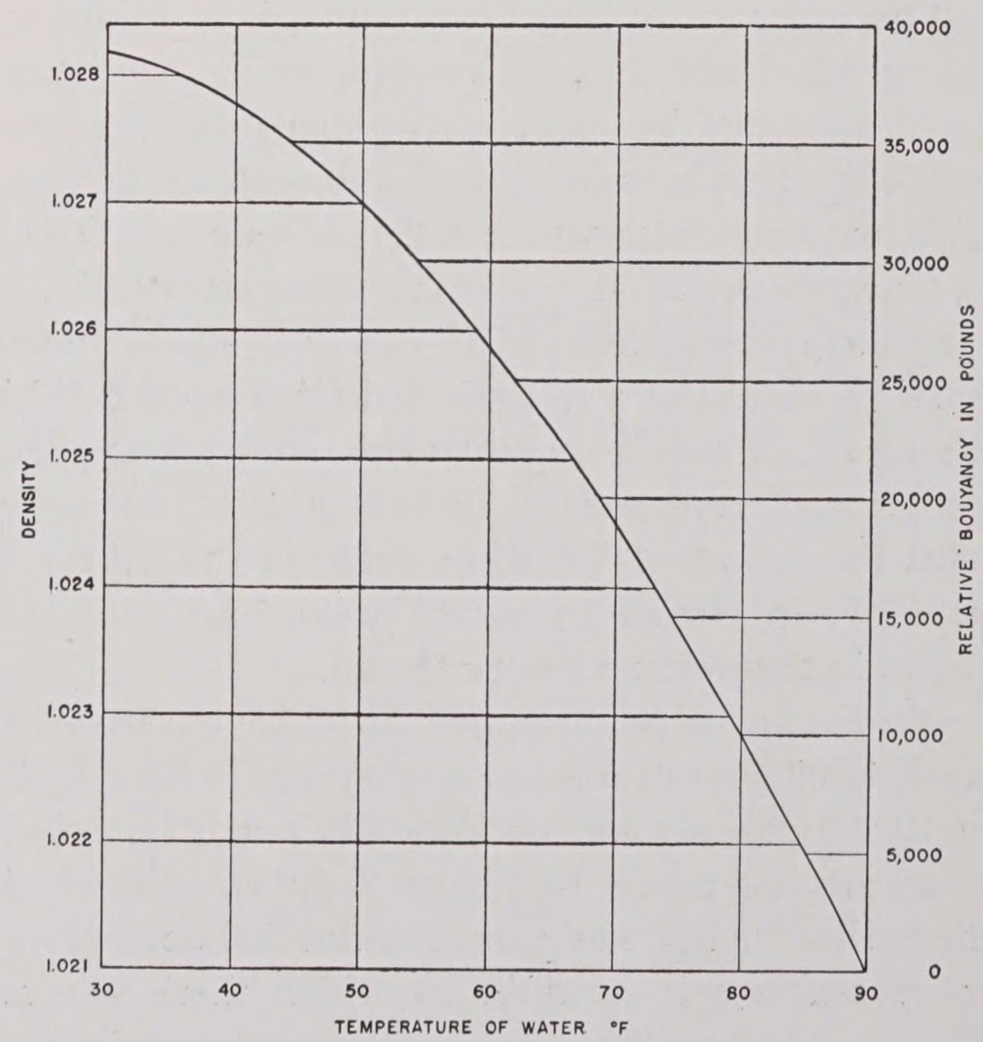


FIGURE 1. Effect of temperature on the density of sea water having a salinity of 35 ‰ and corresponding effect on buoyancy of a submarine of 2,400 tons submerged displacement.

[a] The density function $\rho_{ts}$ is expressed in grams per cubic centimeter. In oceanography the specific gravity of sea water is defined relative to pure water at 4 C. Consequently the numerical values of density and specific gravity are the same and values of $\rho_{ts}$ may be used to express specific gravity. This is done in the practical solution of buoyancy problems as explained in Chapter 4.

water at any one place is far from uniform. Exchanges of heat take place through the sea's surface and additions or losses in water also occur at the surface through precipitation and evaporation. Consequently, temperature and salinity and the resulting density frequently change with depth. On the other hand, water of a given density tends to seek its own level and to spread uniformly for relatively great distances in a horizontal direction. Consequently, the sea has a stratified structure, composed of horizontal layers of different quality lying one upon another.

The maximum change in temperature and salinity which a submarine is likely to encounter in a single dive from periscope depth and the related density and buoyancy changes are about as follows:

| | Maximum change | Resulting density change | Resulting buoyancy change |
|---|---|---|---|
| Temperature | 30 F | 0.00420 | 22,600 pounds |
| Salinity | 2.5 ‰ | 0.00195 | 10,500 pounds |
| Total | | 0.00615 | 33,100 pounds |

These figures bring out the fact that under extreme conditions salinity changes are responsible for only about one-third of the density change likely to be encountered.

The estimate of the maximum likely buoyancy change given above exceeds somewhat the maximum figure recorded by American submarines operating in the Pacific war area which is about 26,000 pounds. The frequency with which different amounts of ballast have been actually pumped out or flooded in, in the course of deep dives while in service under recent wartime conditions, is indicated by Figure 2. This histogram is based on notations on bathythermograph cards returned by 49 submarines and represents the record of 336 dives made in the course of training, in transit to patrol areas, and while on patrol in the western Pacific Ocean.

While the ballast pumped on descent rarely exceeds 4,000 pounds it is not uncommon to flood 8,000 to 10,000 pounds and occasionally much larger adjustments are made. In Figure 2 the class in which the ballast change was plus or minus 500 pounds was composed largely of dives in which there was no change of ballast. This class is of exceptional size and the two adjacent classes are of relative deficiency because small maladjustments of trim are frequently disregarded in diving, and no change in ballast is

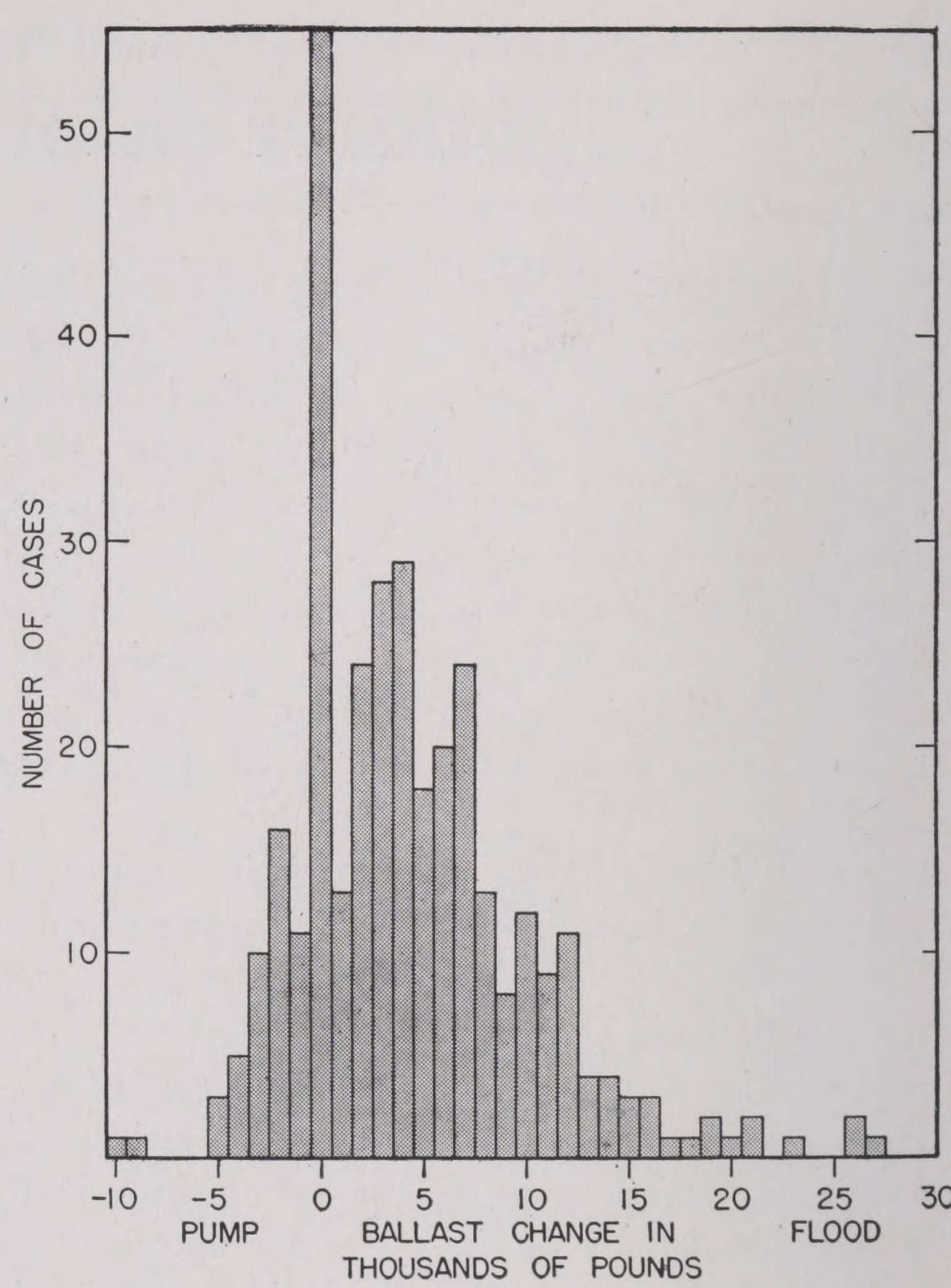


FIGURE 2. Frequency distribution of ballast changes made in deep dives by fleet-type submarines in service.

ordinarily made unless the net buoyancy becomes more than one or two thousand pounds.

## 2.1 STABILITY OF THE WATER COLUMN

Layers of sea water of higher density cannot exist long above layers of lower density since, being heavier, they sink through the lighter layers and mix with them. When conditions arise which increase the density of the surface layers of the sea, such as cooling in the fall of the year or rapid evaporation, mixing processes are set up which tend to bring the surface layers to a condition of homogeneous temperature and salinity. Negative density gradients cannot exist permanently in the sea because the condition is unstable.

On the other hand, if the density of the surface waters is less than that of the deeper layers a stable condition exists which tends to be permanent. Work must be done to cause the lighter layers to mix with those beneath and thus the mixing action of wind and tide are retarded. When conditions are favorable for the formation of stable conditions, such as the warming of the surface waters in early summer, the condition not only persists, but increases because the surface layers are kept from mixing with those beneath and the heat absorbed from the sun and the acquisitions of fresh water from rainfall remain concentrated in the upper layers.

The compression of the water with depth does not influence the stability of the water column. Within such depths as are reached by submarines, the contribution of temperature and salinity to density, $\rho_{ts}$, alone need to be taken into account in determining stability. Stability is defined as the rate of change of density with depth or by $d\rho_{ts}/dZ$ where $Z$ is the depth. Negative values of stability are highly exceptional and cannot exist except as the result of very active processes.

## 2.2 MIXED WATER

Wherever the forces of wind, tide, and current are strong enough to overcome the influences which lead to stable stratification, the sea water becomes thoroughly mixed. The completeness of the process is indicated by the uniformity of the temperature, and such water is frequently referred to as *isothermal.* The thorough mixing indicated by the uniform temperature usually may be assumed to produce a uniform distribution of salinity. Consequently, isothermal water is generally devoid of density gradients.

Shallow isothermal layers exist very generally at the immediate sea surface where wave action mixes the water. Layers extending deep enough to influence submarine operation are more restricted. In the tropical and subtropical oceans deep isothermal layers of warm water occur at the surface which, in the trade wind belts, may extend to three or four hundred feet in depth. In temperate regions the upper layers of the sea are thermally stratified during the summer season, but as the solar radiation weakens in the fall the mixing processes prevail and the mixed layer at the surface grows in depth until it extends by midwinter to 300 feet or more below the surface. The seasonal change in the depth of the mixed water in the North Atlantic in the vicinity of Bermuda is shown in Figure 3.

One situation exists in which density gradients may occur in water which is practically isothermal. In the wet tropics the sea surface may obtain additions of fresh water which are of nearly the same temperature as the sea water. A salinity gradient consequently develops near the surface. Figure 4 illustrates such a condition which has been observed off the west coast of Africa. Although the water was essentially of uniform temperature to a depth of 150 feet a salinity gradient occurred above this depth which increased the density by an amount which would alter the buoyancy of a submarine by 7,500 pounds in the course of a dive to the lower limit of the isothermal layer. Similar conditions have been observed in the southwestern Pacific Ocean.

It is possible that a similar situation may arise along the coasts of temperate regions during early

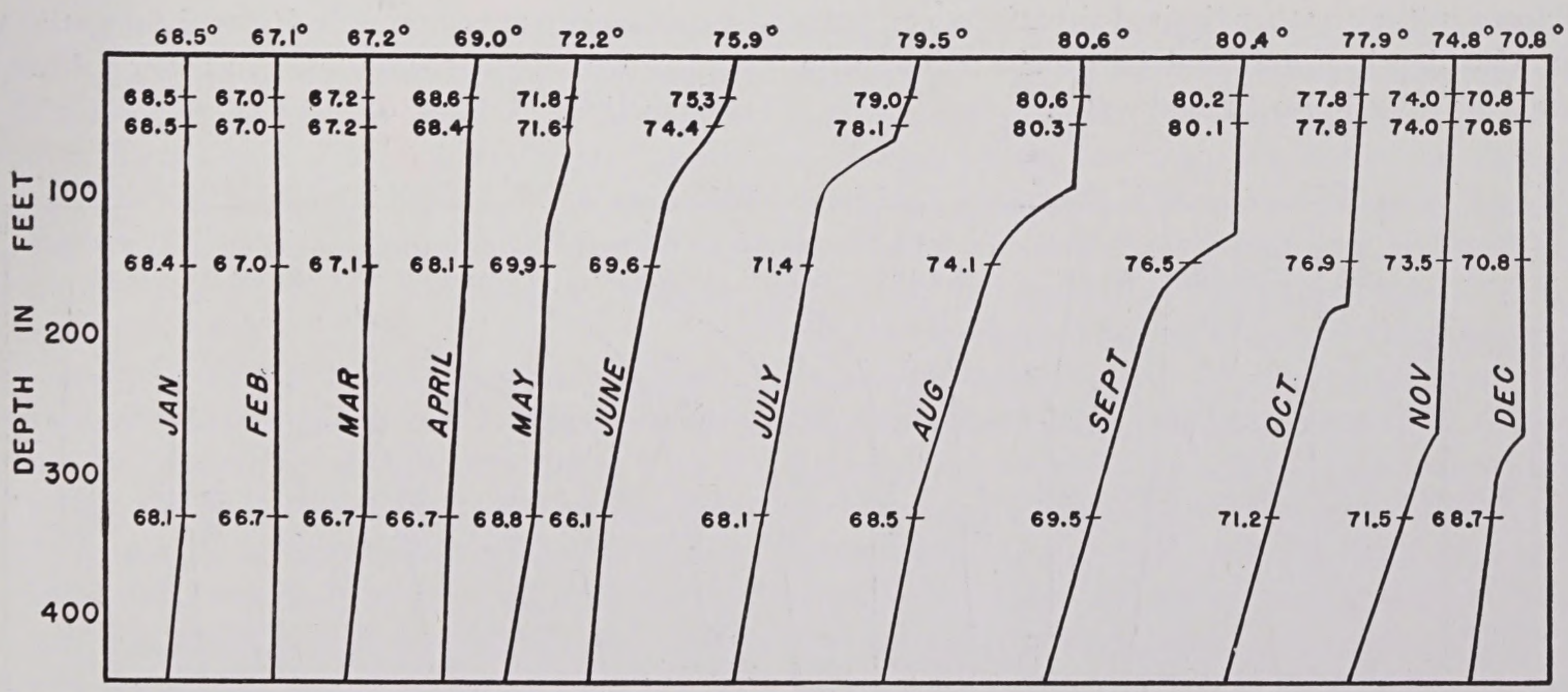


FIGURE 3. Distribution of temperature in the upper layers of the North Atlantic Ocean, in neighborhood of Bermuda throughout the year.

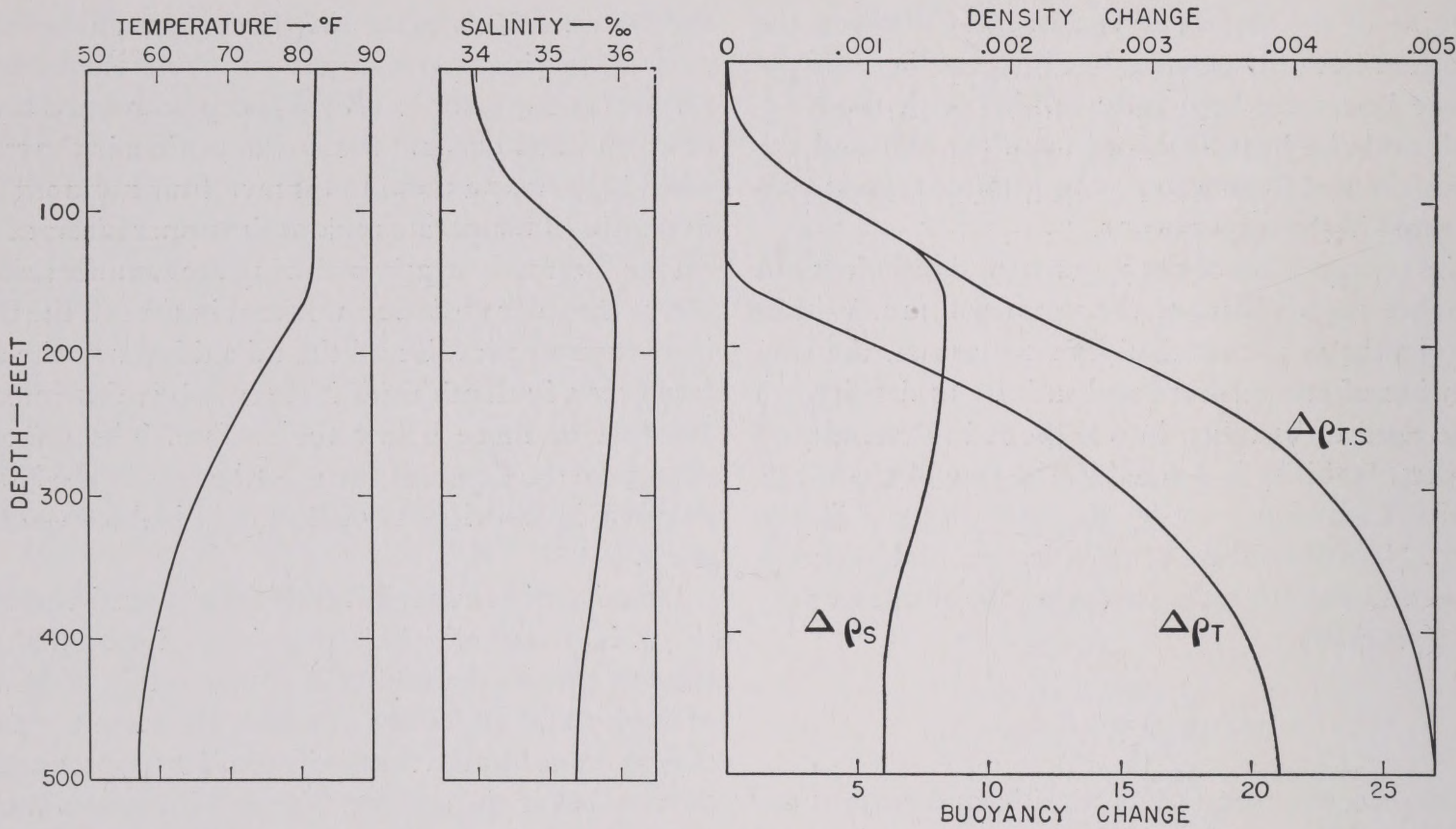


FIGURE 4. Distribution of temperature, salinity, and density in the upper layers of the Atlantic Ocean at 5° 36′ N, 23° 25′ W. $\Delta\rho_t$ shows effect of the temperature gradient, $\Delta\rho_s$ the effect of the salinity gradient, and $\Delta\rho_{ts}$ their combined effect on density. The corresponding effect on the buoyancy of a submerged submarine of 2,400 tons displacement is shown, in thousands of pounds, on the scale marked Buoyancy Change.

spring wherever melting snows bring large quantities of fresh water at nearly freezing temperature into the sea when its temperature also is near freezing point. However, such situations would be very local and temporary and the density gradients produced would probably be too near the surface to affect diving operations.

Except in these rather limited situations, compression with depth alone need be considered when a submarine dives in isothermal water.

## 2.3 NEGATIVE TEMPERATURE GRADIENTS

Sea water is usually warmer at the surface than at some greater depth. The layer of water in which temperature decreases sharply with depth is called the *thermocline*. The strong density layers encountered by submarines are commonly due to the negative temperature gradients encountered in passing through a thermocline.

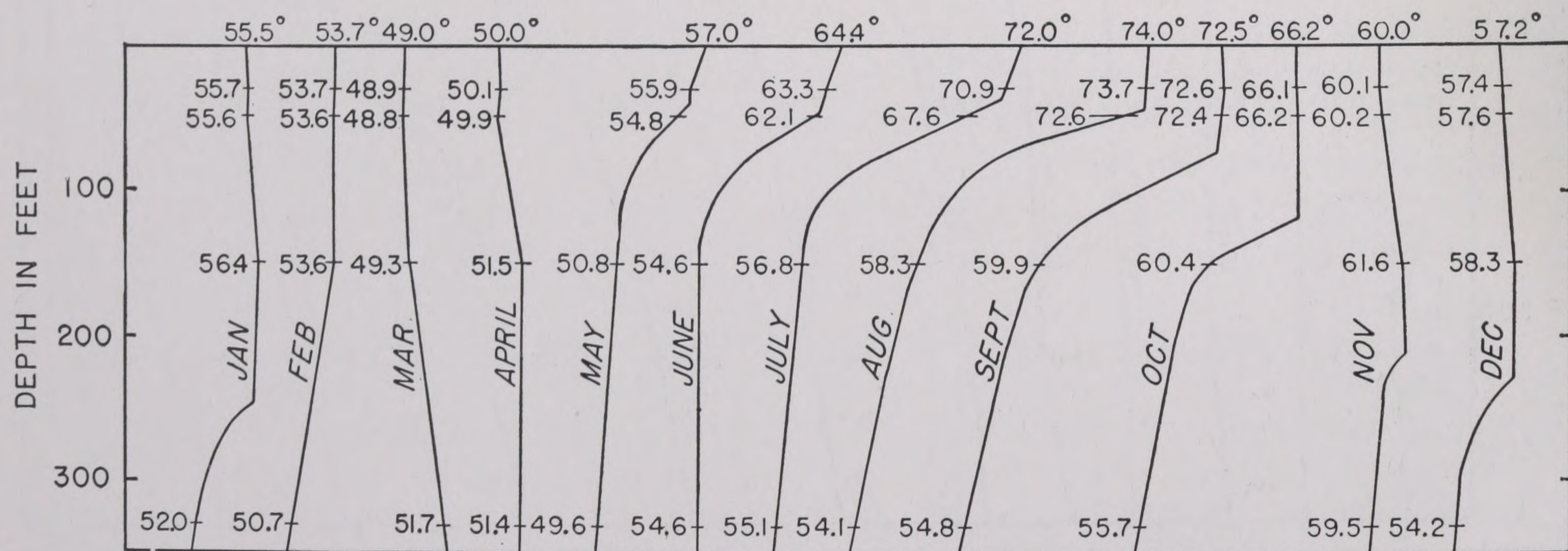


FIGURE 5. Distribution of temperature in the upper layers of the Gulf of Maine throughout the year.

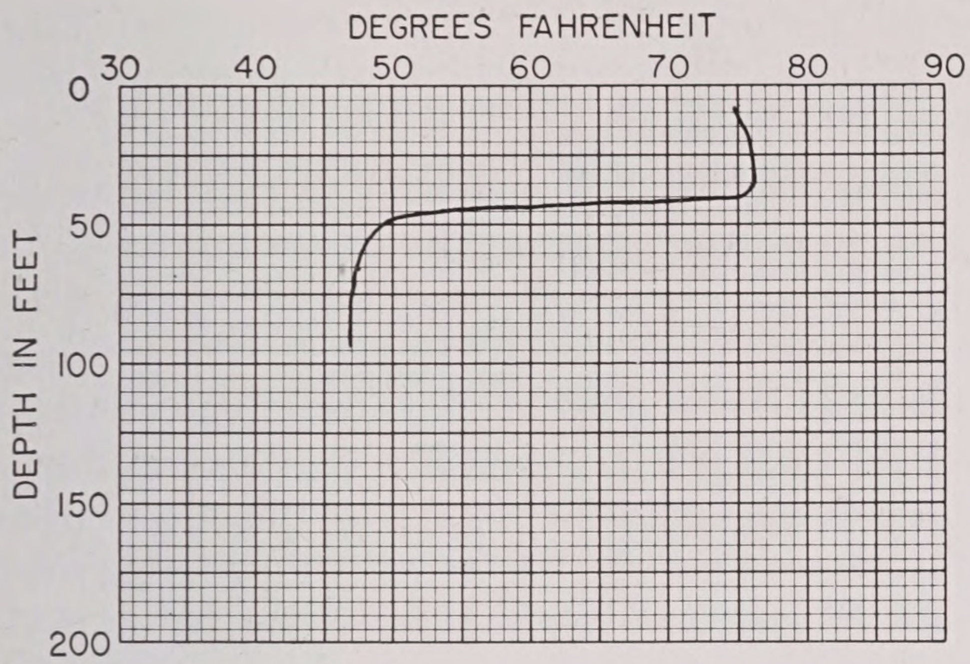


FIGURE 6. Exceptionally strong negative temperature gradient recorded by bathythermograph of a U. S. submarine in the Yellow Sea in September.

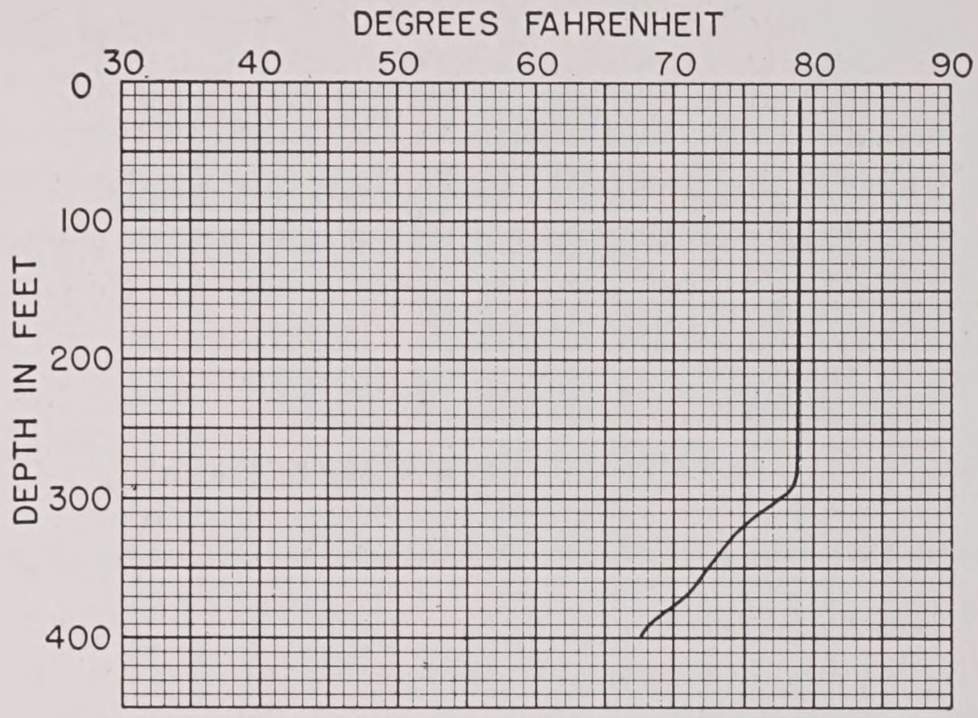


FIGURE 7. A deep-lying negative temperature gradient recorded by bathythermograph of a U. S. submarine in the Japan Current.

Negative temperature gradients arise in two ways; first, the warming of the surface by the sun, and second, the flow of warm water layers over colder masses of water as the result of currents.

In temperate latitudes, where the sea is uniformly chilled in the winter, strong temperature gradients of the first type develop each summer. Their development runs a characteristic course illustrated in Figure 5, the gradients becoming stronger as the season advances and never extending very deep. With the cooling of the surface water in the fall the gradient is rather abruptly destroyed and becomes deeper as this takes place.

Shallow gradients are particularly well developed along the eastern coasts of Asia and North America. The density layers which they produce along the New England coast in summer are familiar to American submariners. Figure 6 illustrates an exceptionally strong gradient of this sort recorded by a submarine operating in the Yellow Sea in September. It was necessary to flood 20,000 pounds of ballast to penetrate below this layer.

The second general type of temperature gradient arises from the circumstance that the basins of the ocean are everywhere filled with cold water. This is water which has been chilled and sunk in high latitudes. In tropical and subtropical regions the surface water is warmed, frequently to about the temperature of the air. The warm layer is always relatively thick, is usually thoroughly mixed, and often extends to greater depths than are reached in submarine operations. The temperature gradients marking the transition are much less abrupt than those found in the shallow summer thermoclines and usually extend downward for several hundred feet, to beyond the limits reached in diving. The thickness of the warm surface layer depends very much on the local character of the ocean currents. In areas toward which the surface waters move (convergences) the warm layer becomes very thick. In areas away from which the surface water is carried by its motion the temperature gradient approaches much closer to the surface.

It may be seen that the two types of temperature gradient which have been described depend on the nature of the climate in which they are established. Wherever cold water is becoming warmer, either because of a change in season or because of the flow of water to warmer regions a shallow gradient, often of great strength, results. The increasing stability of the water as it warms does not permit the water to warm to great depths. Cold currents consequently are characterized by strong shallow temperature gradients. Wherever the climate is warm throughout the year the surface water is heated to considerable depths. If such water is carried to cooler regions in the course of its circulation, heat is lost from the surface. Cooling the surface creates an unstable condition which leads to thorough mixing. The layer of mixed water above the temperature gradient remains thick or is thickened in the process. Warm currents consequently are characterized by deep-lying temperature gradients. An example recorded from the Kuroshio Current off Japan is illustrated in Figure 7.

It should be unnecessary to point out that in many regions much more complicated temperature patterns are found. These arise from the mixing of diverse waters particularly at the junction of currents. However, the two types of temperature gradient described are characteristic of large portions of the sea and the more complicated patterns are usually to be derived from them.

## 2.4 SALINITY GRADIENTS

Salinity gradients arise from (1) the dilution of the surface by rainfall, melting ice, and the run-off from the land, (2) evaporation of water from the sea's surface, and (3) the flow of waters of different salinity over one another as the result of ocean currents.

In temperate regions there is usually an excess of rainfall over evaporation and consequently positive salinity gradients tend to develop beneath the sea's surface. Along the coasts of such regions the outflow from rivers very greatly augments this effect and substantial density gradients result from the dilution of the upper layers of water. It follows that the shallow temperature gradients characteristic of temperate regions in summer are accompanied by salinity gradients. These gradients are particularly strong in coastal regions. Both kinds of gradient cause the water to be more dense as depth increases, that is, they supplement one another in developing the stability of the water column.

It may be observed from Figure 8, which shows the gradient of temperature, salinity, and resulting density in a situation of this sort, that the gradients of temperature and salinity very closely coincide in depth. This arises because the surface waters are prevented from mixing with the deeper waters by the sharp density gradient while both above and below the water mixes more freely. Both gradients consequently tend to develop in the same relation to the resulting density pattern. During the winter when the disappearance of the temperature gradient decreases the stability of the water, the mixing which results destroys the salinity gradient also. In spring the melting of snows and the rainfall characteristic of the season leads to the early development of the salinity gradient. This becomes relatively less important than the temperature gradient in determining the density distribution as the summer season advances.

In warm oceanic areas salinity gradients are less pronounced and thus of minor importance in determining the density distribution in the upper layers of the sea. In substantial areas of small rainfall in the

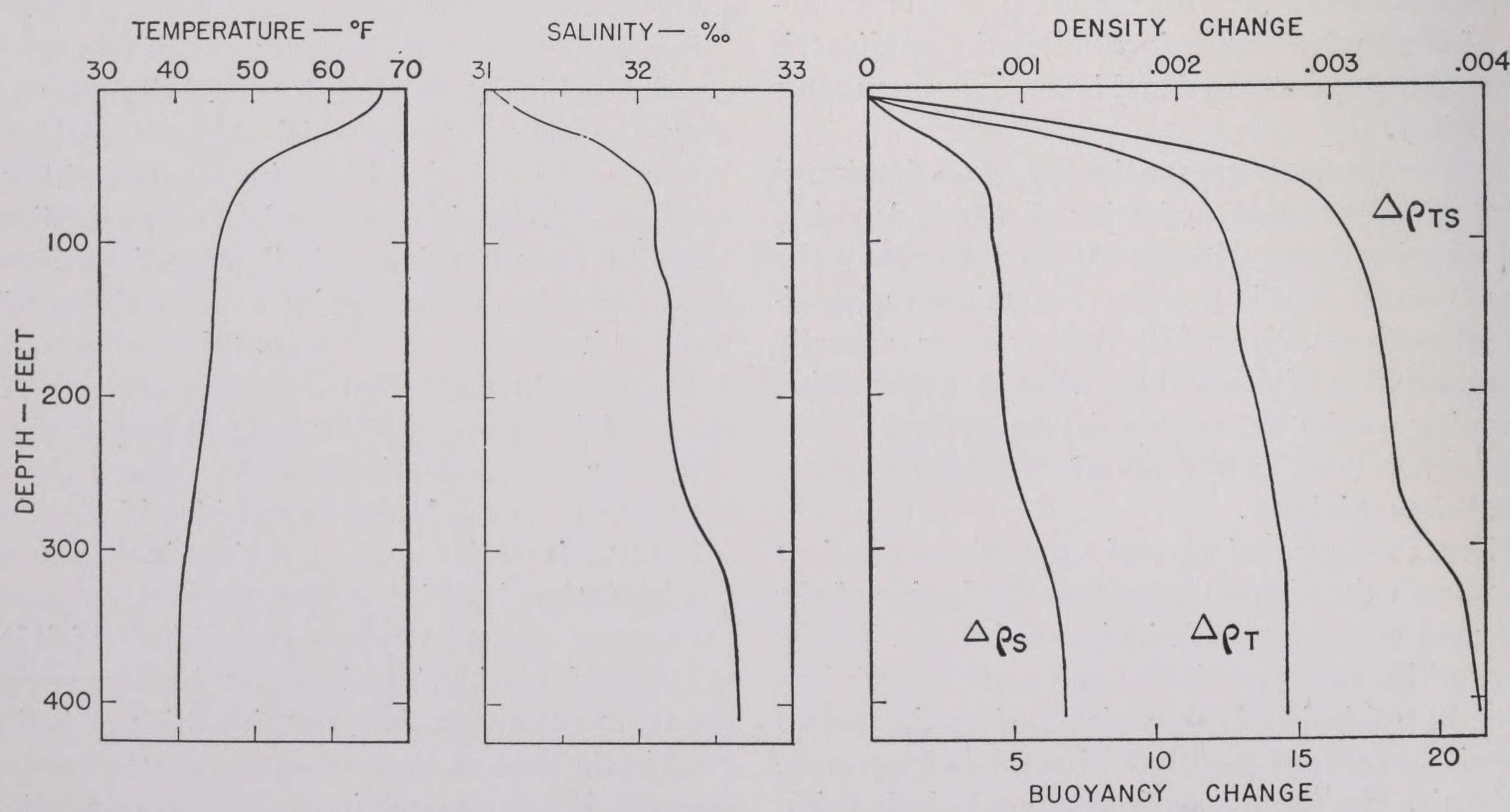


FIGURE 8. Distribution of temperature, salinity, and density in the upper layers of the Gulf of Maine at 42° 55′ N, 70° 15′ W in September. $\Delta\rho_t$ shows the effect of the temperature gradient, $\Delta\rho_s$ the effect of the salinity gradient, and $\Delta\rho_{ts}$ their combined effect on density. The corresponding influence on the buoyancy of a submerged submarine of 2,400 tons displacement is shown, in thousands of pounds, on the scale marked Buoyancy Change.

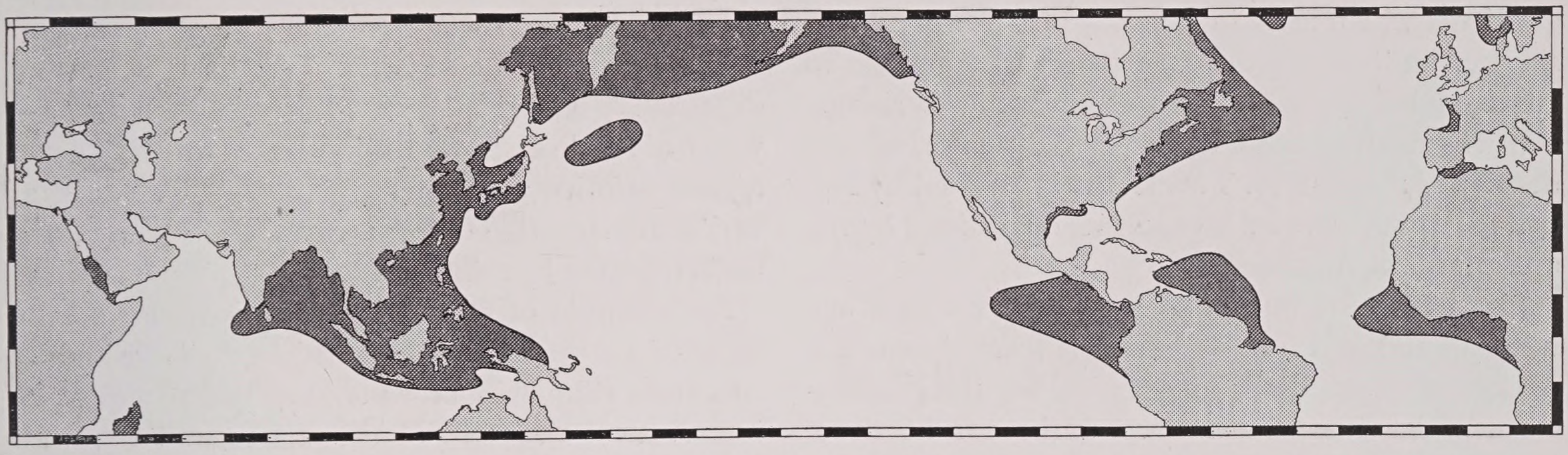

FIGURE 9. Ocean areas where salinity gradients may be expected to influence submarines when diving.

subtropics evaporation exceeds precipitation and the most saline water is found at the surface. Such salinity gradients in the surface layers are small and may be associated with similarly small positive temperature gradients with the result that the density of the water column is nearly uniform. In the wet tropics, on the other hand, rainfall may very substantially reduce the salinity of the surface layers with the result that strong gradients of density are produced. The density layers familiar to submariners operating in the Gulf of Panama are due in part to this. Similar situations are encountered off the west coast of Africa and in the East Indies.

In general, it may be said that salinity gradients play a minor role in producing density gradients large enough to affect submarine operations in the greater part of the open oceans. Along the coasts of temperate regions in the spring and summer and in the wet tropics substantial density gradients result from reduction of the salinity of the surface layers. The areas in which salinity changes are known to occur which produce gradients in density of as much as 0.001 within 300 feet of the surface are shown in Figure 9. Within these areas ballast adjustment of as much as 6,000 pounds may be required in diving for this cause alone.

## 2.5 SALINITY GRADIENTS NEAR RIVER MOUTHS

The fresh water flowing from the mouths of rivers tends to flow over the surface of the sea water, sometimes for very great distances. The strong density

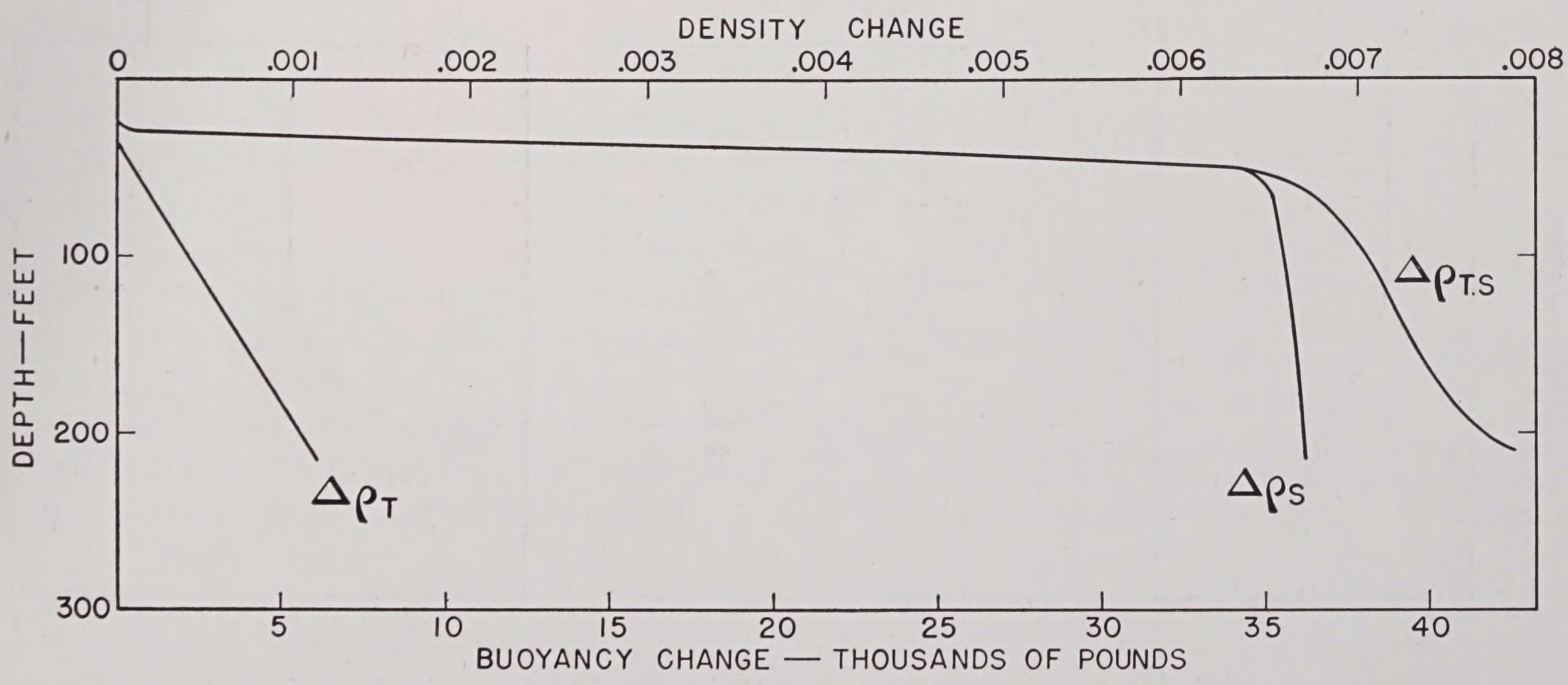


FIGURE 10. Effect of temperature and salinity gradients on density in the upper layers of the Atlantic off the Amazon River at 3° 10′ N, 49° 29′ W. $\Delta\rho_t$ shows the effect of the temperature gradient, $\Delta\rho_s$ the effect of the salinity gradient, and $\Delta\rho_{ts}$ their combined effect. The resulting influence on the buoyancy of a submerged submarine of 2,400 tons displacement is shown on the lower scale.

gradients which arise in this way are, however, very shallow and usually do not extend deep enough to affect submarine operations at or below periscope depth as much as might be expected from the reduced density of the surface. This fact is illustrated by Figure 10, which shows the gradients occasioned by the outflow of the Amazon.

Since currents must flow parallel to coasts, the water of reduced salinity which is formed near the mouths of rivers tends to spread along the coast instead of flowing out to sea. Continuous bands of water of low salinity are consequently formed along coasts in areas of adequate rainfall.

## 2.6 POSITIVE TEMPERATURE GRADIENTS

A positive temperature gradient cannot persist unless accompanied by a positive salinity gradient. This is because in the absence of a salinity gradient the water column will be unstable if the upper layers are colder and thus more dense than those below. The salinity gradient must increase the density with depth at least as much as the positive temperature gradient decreases it if an unstable condition is to be avoided.

Rather weak positive temperature gradients may be produced by the cooling of the surface during the fall and winter in temperate regions when salinity gradients are present. These effects are not large and are too near the surface to concern submarines in diving. More extensive positive gradients at greater depths may be formed by the flow of layers of colder water of relatively low salinity over warmer water of higher salinity at greater depth. The locations at which this situation occurs are limited but happen to be frequented by submarines.

An example of such a situation is found off the coast of southern New England in areas visited by American submarines for purposes of test and training. Near the margin of the continental shelf the coastal water tends to flow out over the deeper oceanic water. The coastal water is much less saline than oceanic water and a pronounced salinity gradient is formed at a depth of 150 to 250 feet. During the winter the coastal water becomes much colder than the deeper layers so that a positive temperature gradient is formed. Although this cooling increases the density of the upper layer the water column remains stable since the salinity gradient more than compensates for the effect of the temperature gradient. The situation is illustrated by Figure 11 which shows the conditions encountered by a submarine in April. The temperature increased 10 F between 150 and 275 feet, yet the density increased 0.0006 in the same depths because of an increase in salinity at the greater depths of 1.9 $^0/_{00}$. The submarine was able to float balanced in the density gradient at 210 feet in spite of the strong positive temperature gradient.

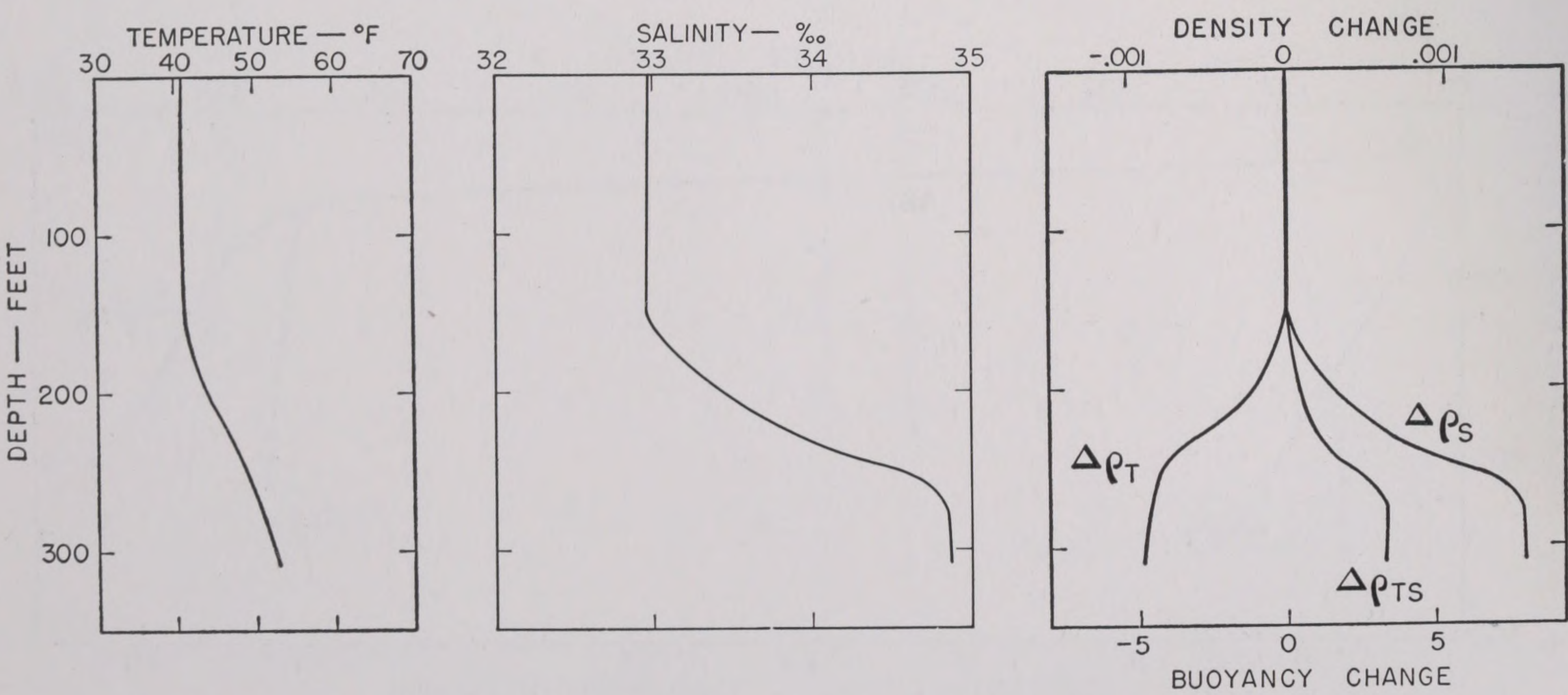


FIGURE 11. Distribution of temperature, salinity, and density in the upper layers of the Atlantic Ocean near the western margin of the Gulf Stream (40° 14′ N, 70° 56′ W). $\Delta\rho_t$ shows effect of the temperature gradient, $\Delta\rho_s$ the effect of the salinity gradient, and $\Delta\rho_{ts}$ their combined effect on density. The corresponding influence on the buoyancy of a submerged submarine of 2,400 tons displacement is shown, in thousands of pounds, on the scale marked Buoyancy Change.

## 2.7 INTERNAL WAVES

Where gradients of temperature or salinity occur in the ocean giving rise to changes in density with depth, it has frequently been observed that the layers of water are in vertical oscillation. These internal waves vary greatly in period and amplitude depending on circumstances. The waves most frequently observed in density gradients within the operating depths of submarines have periods of 10 or 15 minutes. Waves of longer period, from 2 to 12 hours, have also been recorded, the latter apparently being related to the tidal rhythm. The amplitude of the waves is variable. The short-period waves may have amplitudes of 10 to 16 feet; amplitudes as great as 45 to 60 feet have been recorded for the long-period waves.

Internal waves introduce uncertainty into submarine operations in two ways. The passage of a wave during deep submergence may cause quite different ballast adjustments to be required on returning to a given depth within the density gradient than were anticipated from conditions encountered during the preceding descent. Very frequently bathythermograph records on ascent show a quite different trace from that obtained in descent owing to the vertical displacement of the water layers of different temperatures. Figure 12 illustrates a tracing of this character.

A submarine operating in a density layer in which internal waves occur will tend to rise and sink with the wave. This behavior is illustrated in Figure 13 which shows the changes in depth of a submarine while balanced motionless in a density layer off Portsmouth, New Hampshire. The submarine rose and fell with a fairly regular rhythm of period of about 15 minutes. The change in depth varied from 8 to 14 feet and the maximum rate of rise or fall was 2 feet per minute. The observations lasted for over an hour during which time the temperature of water samples drawn from the sea did not vary more than 1 F. Since the submarine lay in a temperature gradient of 0.5 F per foot, it was evident that the entire water mass was rising and falling carrying the vessel with it.

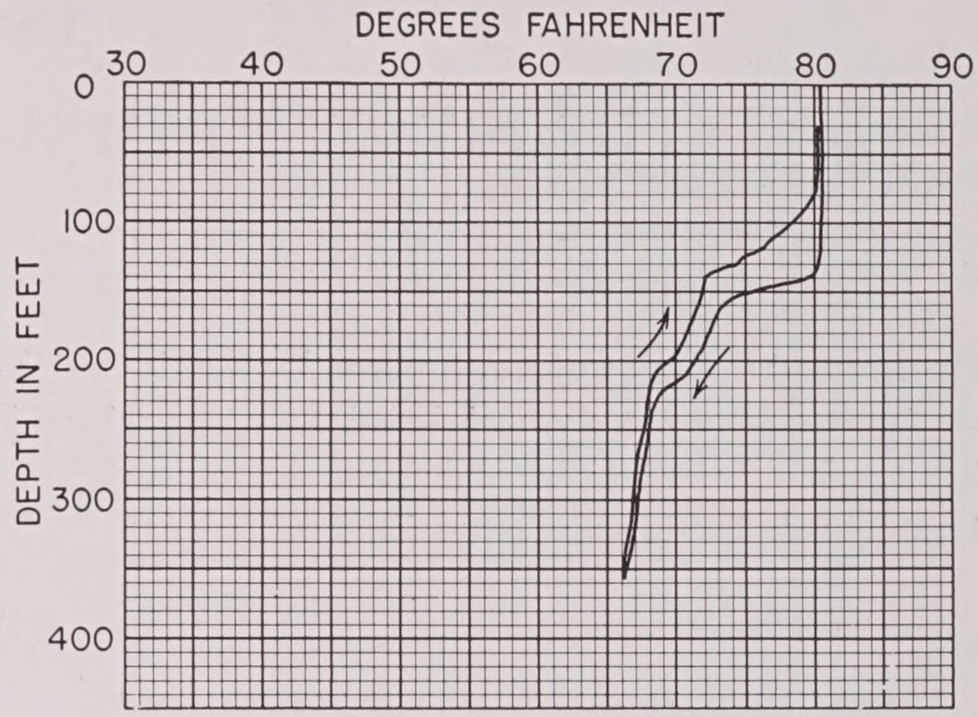


FIGURE 12. Displacement of the temperature trace attributed to the passage of an internal wave during the period of deep submergence, recorded by bathythermograph of U. S. submarine.

When internal waves of this sort are present it is more difficult to maintain constant depth without continual adjustment of diving planes or ballast. This is a serious disadvantage if it occurs while depths suitable for using the periscope must be maintained. During deep submergence when exact depth control is less important, the change in depth due to internal waves may not be inconvenient and the submarine may be allowed to rise and fall with the oscillation of the water.

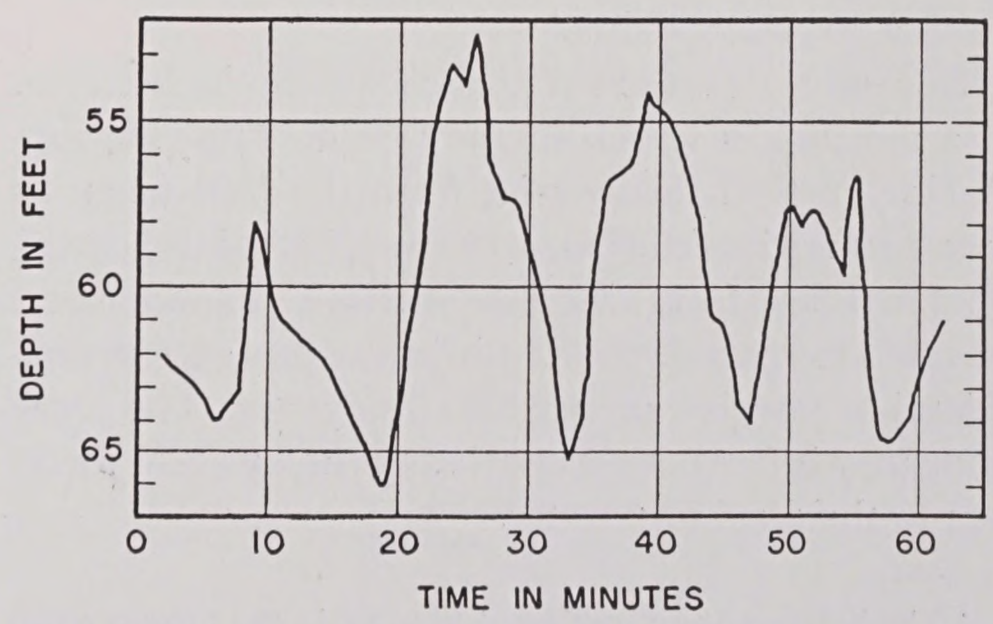


FIGURE 13. Changes in keel depth of a submarine balanced in a density gradient showing vertical oscillation due to the passage of internal waves.

## Chapter 3

# THEORY OF TRIM ADJUSTMENT IN DIVING

### 3.1 BUOYANCY

THE NET buoyancy of a submerged vessel is the difference between the weight of the water which is displaced and the weight of the vessel. Net buoyancy, $B$, may be defined by the equation:

$$B = \rho V - W, \tag{1}$$

in which $\rho$ = density of the water,

$V$ = volume of water displaced by the vessel, and

$W$ = weight of the vessel.

Net buoyancy is *positive* when the displaced weight of water is greater than the weight of the vessel. In this case the vessel tends to rise. Net buoyancy is *negative* when the weight of the displaced water is less than the weight of the vessel, and in this case the vessel tends to sink. If the displaced weight of water equals the weight of the vessel net buoyancy is zero, and buoyancy is said to be *neutral*. The vessel tends neither to rise nor sink.

Buoyancy forces are static and define the behavior of a motionless vessel. In the case of a moving submarine vertical forces arise from the hull form, its fore and aft inclination, and the "lift" of the diving planes. These forces increase with speed and make it possible to control the depth in the presence of considerable positive or negative buoyancy. The word buoyancy is frequently applied to the buoyant force[a] due to the displaced water.

[a] The buoyant force is referred to as $\rho V$ in the present treatment. Since it is convenient to break this term down into several components in the discussion of submarine problems, this restricted use of the word is abandoned and buoyancy is used in place of net buoyancy whenever no ambiguity is involved. The term $\rho V$ will be referred to as the weight displacement.

In the present chapter, net buoyancy and weight are assumed to be measured in grams and volume in cubic centimeters. This avoids the necessity for introducing dimensional constants into the fundamental equations. Conversion to the practical units employed in naval architecture and marine engineering are discussed in Chapter 4.

### 3.2 EFFECT OF CHANGE IN DEPTH

If the submarine dives to a different depth the change in depth is attended with the following changes:

$\triangle B$ = change in net buoyancy,

$\triangle V$ = change in volume displacement due to compression of the hull with depth,

$\triangle \rho$ = change in density of the sea water,

$\triangle W$ = change in weight due to ballast adjustments or any other cause.

The relation of these changes for any change in depth, $Z$, may be derived from equation (1) and are as follows:

$$\triangle B = \rho \triangle V + V \triangle \rho - \triangle W. \tag{2}$$

$\triangle \rho$ is the sum of two quantities, $\triangle \rho_z$ and $\triangle \rho_{ts}$ which may be defined as follows:

$\triangle \rho_z$ = change in density of sea water due to compression with depth.

$\triangle \rho_{ts}$ = change in density of sea water due to changes in temperature and salinity.

$V \triangle \rho$ may consequently be written $V \triangle \rho_z + V \triangle \rho_{ts}$ and equation (2) becomes:

$$\triangle B = \rho \triangle V + V \triangle \rho_z + V \triangle \rho_{ts} - \triangle W. \tag{3}$$

The first two terms of this equation represent respectively the effect on the net buoyancy of compression of the hull and of sea water with depth. The change in volume of the hull may be assumed to be a linear function of depth. The change in density of sea water is known to be essentially a linear function of depth which amounts to $1.42 \times 10^{-6}$ gm per cu cm per foot.

The total effect of compression on net buoyancy is



[redacted]

consequently a linear function of depth and may be expressed by the term $C\triangle Z$ in which $C$ is the coefficient of compression, i.e., of buoyancy change per unit increase in depth. Hence, $C\triangle Z = \rho\triangle V + V\triangle\rho_z$. Substituting in equation (3)

$$\triangle B = V\triangle\rho_{ts} + C\triangle Z - \triangle W. \qquad (4)$$

This is the fundamental equation for estimating buoyancy changes in diving.

## 3.3 TRIM

Submariners employ the term *trim* to designate the adjustment of buoyancy as required by the conditions of operation.[b] *Good trim* at any stated speed may be defined as the condition where the vessel may be held at the desired depth with minimal adjustment of the angle of hull and diving planes. The positive or negative buoyancy which is consistent with *good trim* decreases rapidly as speed is reduced and at 2 knots is about 500 pounds. *Stop trim* is the condition obtained when buoyancy is neutral and the submarine holds its depth in the absence of the planing forces dependent on motion.

In the case of a submarine in stop trim $\triangle B = 0$ and equation (4) becomes

$$\triangle W = V\triangle\rho_{ts} + C\triangle Z. \qquad (5)$$

This is the fundamental equation for estimating ballast adjustments in diving.

In applying equation (5) it should be remembered that each term represents an effect on net buoyancy. The coefficient of compression $C$ is always *negative* since the loss in buoyancy due to compression of the hull of existing submarines is always greater than the gain in buoyancy due to compression of sea water. Consequently $C\triangle Z$ is a negative quantity on descent and a positive quantity on ascent; $\triangle\rho_{ts}$ may equal zero or may increase with increasing depth. For hydrostatic reasons it never decreases with depth. Since buoyancy increases in proportion to $V$, $V\triangle\rho_{ts}$ is a positive number on descent and a negative number on ascent, except when it equals zero.

[b] As employed here, trim refers specifically to what is more exactly stated as *overall* trim and depends upon the total weight of the submarine. Trim is also used to designate the distribution of weight relative to the center of buoyancy, e.g., to the fore and aft trim.

The term $\triangle W$ is the change in weight required to re-establish trim, that is, to nullify the buoyancy changes due to the other terms. Consequently, when buoyancy increases $W$ must also increase. That is, positive values of $\triangle W$ indicate ballast to be flooded in; negative values of $\triangle W$ indicate ballast to be pumped out.

The following rules may be deduced from equation (5) for predicting the nature of ballast adjustments.

1. When $\triangle\rho_{ts} = 0$

$$\triangle W = C\triangle Z.$$

Remembering that $C$ is a negative number, ballast must be pumped out on descent or flooded in on ascent in proportion to the change in depth, if density gradients are not present.

2. When $V\triangle\rho_{ts} > -C\triangle Z$

$\triangle W$ is positive on descent; negative on ascent.

If the density gradient has a larger effect on buoyancy than the compression effect ballast must be flooded in on descent and pumped out on ascent.

3. When $V\triangle\rho_{ts} < -C\triangle Z$

$\triangle W$ is negative on descent; positive on ascent.

If the density gradient has a smaller effect on buoyancy than the compression effect ballast must be pumped out on descent and flooded in on ascent.

4. When $V\triangle\rho_{ts} = -C\triangle Z$

$$\triangle W = 0.$$

If the density gradient has an effect on buoyancy equal to the effect of compression with depth no ballast change is required in changing depth. This case is known as the *isoballast condition.*

The quantitative solution of problems in ballast adjustment requires the numerical evaluation of (1) the coefficient of compression characteristic of the vessel in question, and (2) observations on the density of the water in which it is diving.

## Chapter 4

# PRACTICAL UNITS AND RELATIONS

### 4.1 THE BALLAST CHANGE

THE BALLAST change, $\Delta W$, is expressed as the weight of water in pounds in conformity to submarine practice. Ballast flooded is $+ \Delta W$; ballast pumped is $- \Delta W$.

### 4.2 THE DISPLACEMENT

In naval architecture displacement is customarily expressed as the weight of water displaced by the vessel. In practical considerations of buoyancy it is consequently convenient to redefine $V$ as the weight displacement of the vessel, instead of as the volume displacement as was done in the preceding chapter. If at the same time $\rho$ is redefined as the specific gravity of the sea water, instead of the density, the term $V\rho$ will retain its original dimensions and the equations previously developed may be applied.

In oceanography the term density is commonly applied to the specific gravity of sea water relative to that of distilled water at 4 C. According to this convention specific gravities (relative densities) and true density (in grams per cubic centimeter) are numerically equal, and the same values of $\rho$ may be used to represent either without numerical inconsistency. The values of specific gravity according to this usage are about 0.001 lower than those commonly employed in naval architecture which are referred to the density of pure water at 60 F. Thus, weight displacement is commonly estimated assuming the specific gravity of sea water to be 1.025, which corresponds to a specific gravity, or density, of 1.024 according to oceanographic usage.

It is often convenient when tabulating data to use a special notation in which density, $\rho$, is expressed by the symbol $\sigma$ which is defined in the following manner:

$$\sigma = (\rho - 1)\ 1{,}000.$$

Thus, if $\rho = 1.0258$, $\sigma = 25.8$. The markings of hydrometer scales are frequently abbreviated similarly.

The symbol $\sigma_t$ is used to designate the $\sigma$ value of a sample of sea water of some given temperature and salinity when measured at atmospheric pressure. The $\sigma_t$ values correspond to $\rho_{ts}$ as used in equation (5) of Chapter 3. These values do not take account of the effect of pressure at depth on the density of sea water *in situ*.

The weight displacement is commonly stated in tons, for which purpose the long ton of 2,240 pounds is employed. In considering submarine buoyancy problems it is more convenient to express displacement in pounds, since ballast changes are measured in this unit.

For a modern fleet-type submarine the weight displacement submerged is 2,400 tons or $V = 5.4 \times 10^6$ pounds.

### 4.3 THE EFFECT OF DENSITY ON BUOYANCY

The effect of density on buoyancy, $V\Delta\rho_{ts}$, is given for a fleet-type submarine by: $5.4 \times 10^6 \times$ change in density. It must be assumed that the layers of sea water in which the displacement lies are uniform and similar to the sample measured. Since this may not be the case, samples should be drawn from near the level of the center of buoyancy to secure the best representative value.

### 4.4 RELATION OF SALINITY TO DENSITY

Salinity is expressed as grams of salt per 1,000 grams of sea water. The density of sea water is increased by 0.00078 when the salinity increases $1\,^0/_{00}$. An increase of salinity of $1\,^0/_{00}$ requires the flooding of $.00078 \times 5.4 \times 10^6 = 4{,}200$ pounds of ballast. This relation is sufficiently correct at temperatures between 30 and 90 F.

### 4.5 RELATION OF TEMPERATURE TO DENSITY

The density of sea water decreases as the temperature increases. The curve describing this relation for water of $S = 35\,^0/_{00}$ is shown in Figure 1 of Chapter 2. Within the range of salinity commonly encountered in the open sea, that is, 30 to $35\,^0/_{00}$, the change in density produced by any change in temperature does not vary greatly with salinity. Consequently, the curve in Figure 1 can be used to describe with sufficient accuracy the relative buoyancy of a 2,400-ton submarine when submerged in water of different temperature but of any constant salinity above 30 $^0/_{00}$.

The following figures show the approximate effect of an increase in temperature of 1 degree on the density of sea water and on the buoyancy of a submarine of 2,400-ton submerged displacement in sea water of $35^0/_{00}$ salinity at characteristic temperatures.

| Temperature F | Density change per 1 F | Buoyancy change in lb per 1 F |
|---|---|---|
| 40 | −0.000060 | −320 |
| 60 | −0.000124 | −670 |
| 80 | −0.000175 | −940 |

For fresh water the corresponding figures are:

| Temperature F | Density Change per 1 F | Buoyancy Change in lb per 1 F |
|---|---|---|
| 40 | 0 | 0 |
| 60 | −0.000085 | −460 |
| 80 | −0.000151 | −690 |

Complete data on the relation of temperature and salinity to density are given in Table 1.

## 4.6 RELATION OF COMPRESSION OF SEA WATER TO DENSITY

The density of sea water is increased by compression by approximately 14.2 x $10^{-7}$ per foot of depth at 60 F. The value varies slightly with temperature,

TABLE 1. Density of Sea Water as a Function of Temperature and Salinity.

Temperature F

| Salinity $^0/_{00}$ | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | −0.22 | −0.05 | 0.00 | −0.08 | −0.27 | −0.57 | −0.96 | −1.42 | −2.00 | −2.65 | −3.37 | −4.16 | −5.01 |
| 2 | 1.45 | 1.61 | 1.63 | 1.54 | 1.33 | 1.02 | 0.62 | 0.13 | −0.45 | −1.10 | −1.84 | −2.64 | −3.49 |
| 4 | 3.08 | 3.21 | 3.22 | 3.11 | 2.89 | 2.56 | 2.15 | 1.65 | 1.06 | 0.40 | −0.34 | −1.15 | −2.02 |
| 6 | 4.71 | 4.81 | 4.80 | 4.68 | 4.45 | 4.11 | 3.68 | 3.18 | 2.58 | 1.91 | 1.16 | 0.34 | −0.53 |
| 8 | 6.34 | 6.44 | 6.41 | 6.26 | 6.00 | 5.66 | 5.22 | 4.70 | 4.09 | 3.41 | 2.66 | 1.83 | 0.95 |
| 10 | 7.95 | 8.03 | 7.98 | 7.82 | 7.57 | 7.19 | 6.74 | 6.21 | 5.60 | 4.91 | 4.15 | 3.32 | 2.43 |
| 12 | 9.58 | 9.63 | 9.57 | 9.39 | 9.10 | 8.74 | 8.27 | 7.73 | 7.10 | 6.40 | 5.64 | 4.79 | 3.90 |
| 14 | 11.20 | 11.23 | 11.16 | 10.96 | 10.67 | 10.28 | 9.81 | 9.25 | 8.62 | 7.91 | 7.15 | 6.29 | 5.38 |
| 16 | 12.83 | 12.84 | 12.74 | 12.53 | 12.21 | 11.82 | 11.33 | 10.77 | 10.13 | 9.42 | 8.63 | 7.78 | 6.86 |
| 18 | 14.43 | 14.43 | 14.32 | 14.09 | 13.76 | 13.35 | 12.85 | 12.29 | 11.63 | 10.90 | 10.12 | 9.26 | 8.34 |
| 20 | 16.07 | 16.05 | 15.90 | 15.67 | 15.33 | 14.90 | 14.39 | 13.81 | 13.15 | 12.42 | 11.62 | 10.75 | 9.82 |
| 22 | 17.67 | 17.63 | 17.47 | 17.21 | 16.87 | 16.43 | 15.91 | 15.31 | 14.65 | 13.90 | 13.09 | 12.22 | 11.29 |
| 24 | 19.29 | 19.23 | 19.06 | 18.79 | 18.42 | 17.98 | 17.44 | 16.84 | 16.17 | 15.41 | 14.59 | 13.71 | 12.79 |
| 26 | 20.90 | 20.82 | 20.63 | 20.36 | 19.98 | 19.51 | 18.97 | 18.36 | 17.67 | 16.91 | 16.08 | 15.20 | 14.27 |
| 28 | 22.51 | 22.42 | 22.21 | 21.91 | 21.52 | 21.04 | 20.49 | 19.87 | 19.17 | 18.41 | 17.58 | 16.69 | 15.74 |
| 30 | 24.15 | 24.03 | 23.80 | 23.50 | 23.09 | 22.60 | 22.04 | 21.41 | 20.70 | 19.92 | 19.09 | 18.20 | 17.24 |
| 32 | 25.75 | 25.62 | 25.38 | 25.08 | 24.64 | 24.13 | 23.56 | 22.92 | 22.21 | 21.43 | 20.59 | 19.69 | 18.73 |
| 34 | 27.36 | 27.22 | 26.97 | 26.63 | 26.20 | 25.68 | 25.10 | 24.45 | 23.73 | 22.94 | 22.09 | 21.18 | 20.22 |
| 36 | 28.98 | 28.82 | 28.55 | 28.20 | 27.75 | 27.22 | 26.63 | 25.98 | 25.24 | 24.45 | 23.59 | 22.68 | 21.72 |
| 38 | 30.60 | 30.43 | 30.15 | 29.77 | 29.32 | 28.78 | 28.18 | 27.51 | 26.77 | 25.96 | 25.10 | 24.19 | 23.22 |
| 40 | 32.24 | 32.03 | 31.73 | 31.36 | 30.89 | 30.34 | 29.72 | 29.03 | 28.29 | 27.48 | 26.62 | 25.70 | 24.73 |

The values for density are given as $\sigma_t$ values. Density at a pressure of one atmosphere, $\rho_{ts}$, is obtained from the relation

$$\rho_{ts} = \frac{1{,}000 + \sigma_t}{1{,}000}.$$

being greater at lower temperatures. It may be assumed to be independent of salinity within the salinity range encountered at sea. Since the ballast tanks are open to the sea, the water they contain is compressed equally with that which they displace. Only the pressure hull, which has a displacement of about $3.6 \times 10^6$ pounds resists compression. Consequently the buoyancy of a submarine is increased $14.2 \times 10^{-5} \times 3.6 \times 10^6 = 512$ pounds per 100 feet of increased depth as a result of the compression of the displaced sea water.

Fuel oil ballast, however, has a compression about twice that of sea water. With increase in depth a small amount of sea water will enter the fuel ballast tanks and somewhat reduce the buoyancy. Taking the compression of fuel oil to be $2.8 \times 10^{-6}$ per foot and its density to be 0.8 that of sea water it may be estimated that the buoyancy of a submarine is decreased 78 pounds per 100 feet descent for each 100 tons of fuel oil carried. With a maximum load of 400 tons fuel oil, this effect will amount to about 300 pounds per 100 feet. This effect cannot be estimated usefully since the quantity of fuel oil present is variable.

The magnitude of the effect of compression of sea water in increasing buoyancy can only be rather roughly set at about 500 pounds per 100 feet descent because of the variable amounts of fuel oil carried.

## 4.7 THE COEFFICIENT OF COMPRESSION

The coefficient of compression, $C$, expressing the combined effect on buoyancy of the compression of sea water and of the vessel with depth, is conveniently defined in relation to a change in depth of 100 feet. When so defined, it will be referred to as the *compression* and is expressed as pounds per 100 feet.

$$\text{Compression} = (\triangle W - V\triangle\rho_{ts})\,100/\triangle Z. \qquad (1)$$

For a fleet-type submarine of 2,400 tons submerged displacement,

$$\text{Compression} = (\triangle W - 5.4 \times 10^6 \triangle\rho_{ts})\,100/\triangle Z. \qquad (2)$$

Compression always has a negative value, since it represents a loss of buoyancy with depth. The numerical value is frequently expressed without sign, the negative character of the coefficient being understood.

The term *Diving Rule* is used as a synonym for the compression.

# Chapter 5

# COMPRESSION

When a submarine dives its buoyancy changes for two reasons. As the hydrostatic pressure increases with depth the water becomes more dense because it is compressed. It has been pointed out in Section 4.6 that this effect increases the buoyancy of a submerged submarine of 2,400 tons displacement by about 500 pounds per 100 feet. The hydrostatic pressure also compresses the hull of the submarine so that its displacement becomes less. This leads to a decrease in the buoyancy of the submarine. The net change in buoyancy which must be compensated for by adjusting the variable ballast is thus the difference between that required by the compression of the sea water and that resulting from the compression of the hull.[a]

It is possible to obtain a reasonably satisfactory estimate of the total change in buoyancy due to compression effects by observing the ballast change required to maintain good trim on changing depth. If this estimate is corrected for the effect of changes in density of the water arising from temperature and salinity differences, the resulting figure may be taken to represent the compression resulting from the combined effect on the volume displacement of the hull and the compressibility of sea water. Since the latter is known approximately the true hull compression may be estimated if desired. For most practical purposes, however, it is the resultant effect of the simultaneous compression of the hull and of the sea water which needs to be known.

The coefficient of compression $C$ is defined by equation (1) Section 4.7 as:

$$C = (\triangle W - V\triangle\rho_{ts})\ 100/\triangle Z$$

and the characteristic value of the compression of a fleet-type submarine is given, in pounds per 100 feet change in depth by:

$$(\triangle W - 5.4 \times 10^6 \triangle\rho_{ts})\ 100/\triangle Z$$

where $\triangle Z$ is change in depth in feet.

[a] The effect of the compression of fuel oil discussed in Section 4.6 is difficult to take into account because of the different amounts of oil which will be present from time to time. Since it is not large it has been overlooked or neglected in most of the studies made to date.

## 5.1 THE MEASUREMENT OF COMPRESSION

In order to measure the compression of a submarine, the vessel is trimmed at periscope depth (keel depth about 60 feet) or in case of rough weather at the least depth practicable (usually 100 feet). The content of all variable ballast tanks is recorded and a sample of sea water is collected for the determination of its density. The submarine is then taken to the greatest depth practicable and trimmed and the same data are secured. Finally the submarine is trimmed near the surface and the required data recorded once more.

The estimation of compression from data obtained in this way is illustrated in Table 1.

Table 1. Data Illustrating the Estimation of Compression.

| | | | |
|---|---|---|---|
| Observations | | | |
| Depth | 65 ft | 265 ft | 65 ft |
| Temperature | 57.5 F | 53.0 F | 58.0 F |
| Density | 1.0246 | 1.0250 | 1.0246 |
| Calculation | | | |
| Ballast Change $(\triangle W)$ | | −2,000 lb | +1,500 lb |
| Depth Change $(\triangle Z)$ | | 200 ft | −200 ft |
| Density Change $(\triangle\rho_{ts})$ | | +0.0004 | −0.0004 |
| Density Effect $(5.4 \times 10^6 \triangle\rho_{ts})$ | | +2,160 lb | −2,160 lb |

Descent

$$\text{Compression} = (\triangle W - 5.4 \times 10^6 \triangle\rho_{ts})\ 100/\triangle Z = (-2{,}000 - 2{,}160)\ 100/200 = -2{,}080 \text{ pounds per 100 feet}$$

Ascent

$$\text{Compression} = (+1{,}500 + 2{,}160)\ 100/-200 = -1{,}830 \text{ pounds per 100 feet}$$

Mean compression for ascent and descent = −1,955 pounds/100 feet.

### 5.1.1 Measurement of Density of Sea Water

Samples should be drawn from a water line opening immediately to the sea from the approximate level of the center of buoyancy of the submarine. Either the pressure gauge line in the forward torpedo room or the line supplying the officers' head is suitable. Lines drawn from ballast tanks or heated by machinery are unsuitable.

Density is most precisely determined by calculation from chemical analysis of salinity and measurements of the temperature of the water. The temperature should be taken *immediately on collection* and should be correct to 0.2 F.

Satisfactory measurements of density may be made with a floating hydrometer provided care is taken to secure readings before the temperature of the water has changed. The presence of air bubbles adhering to the hydrometer must be scrupulously avoided. Suitable hydrometers called "Marine Hydrometers" have been designed for this purpose.[b] Specific gravity hydrometers designed for a range 1.02 to 1.03 may also be employed. These do not read the density, as defined in Section 4.2, correctly. The scale values of a specific gravity hydrometer is referred usually to the density of water at 60 F while that of a density hydrometer is referred to water of 4 C. Differences in density are, however, essentially the same as differences in specific gravity and the absolute values of the scale are consequently unimportant.

If means of measuring the density of the water are not available, useful measurements of compression may be made by selecting a place where the water is thoroughly mixed so that density gradients are not present. The compression is then given directly by the amount of ballast pumped per 100 feet descent. If the temperature does not change more than 1 F per 200 feet, it is probable that the salinity will also be uniform and the density correction will be less than 500 pounds per 100 feet which is about the limit of accuracy of the procedure. Such conditions may be found in temperate latitudes during the winter and may also be found in many parts of the subtropical oceans at all seasons.

If tests are made in fresh water the density may be obtained simply from a measure of temperature. The relation between temperature and density of fresh water may be obtained from Table 1 of Chapter 4, using the values of Salinity = 0. The relation differs significantly from that characteristic of salt water and consequently the curve shown in Figure 1, Chapter 2, should not be employed.

## 5.1.2 Establishment of Trim

In securing trim at each depth great care is required. The speed of the vessel should not exceed 40 turns or 2 knots and ballast should be adjusted so that constant depth is held with a hull angle less than 1 degree and diving plane angles less than 5 degrees. It is possible to adjust ballast correctly to within about 500 pounds in this way. At speeds much greater than 2 knots, depth may be controlled with the planes when trim is far from perfect and the results of the test will be unsatisfactory.

Trim should be established and observations made at two depths as far apart as possible so that the errors of measurement will be minimized when they are divided by the change in depth. When compression is determined during routine deep-submergence tests, in which it is customary to level off at a series of increasing depths, it is desirable to secure good trims and a measure of the density of the water at each depth. It is then possible to select the most favorable levels for use in computing compression.

It is undesirable to use data secured when the submarine lies in a strong density gradient. Under this circumstance the density of the water may vary greatly at the various depths occupied by the hull. A sample of water drawn under these conditions may not represent fairly the mean density of the layers in which the displacement lies.

## 5.1.3 Venting Tanks

Before a compression test is made all tanks should be carefully vented to remove the last traces of entrapped air. Air bubbles are highly compressible and if they are carried down by the submarine the test will yield erroneously high values for compression. See Section 5.3 below.

It is preferable that the vents be closed during the test so that the water enclosed in the main ballast tanks before descent will not be replaced in part by denser water into which the submarine may descend, since this would also lead to erroneously increased values for compression.[c]

## 5.1.4 Changes in Weight Due to Leakage

Care should be taken that the weight of the vessel is not altered by factors which are not taken into account such as pumping the bilges or the sanitary tank,

[b] Manufactured by Nurnberg Thermometer Company, Inc., Brooklyn, New York, for the Bureau of Ships.

[c] The relation of the vents to changes in the temperature of the ballast water and its effect on the buoyancy of a submarine are discussed in Chapter 7.

blowing safety tank, or flooding negative tank during the tests.

Leakage is a very serious source of error, particularly when the tests are made on a new vessel during deep-submergence tests. New submarines frequently leak extensively and since the tests require several hours, the increase in weight may be very large. It is not uncommon for such a vessel to need to pump ballast both on descent and ascent since the leakage may be greater than the ballast change required because of compression.

Two procedures are available for dealing with the effects of leakage. One is to be sure that the bilges are pumped dry before each trim is established. The other is to assume that leakage is the same during descent and ascent and to average the values for the coefficient of compression.

Because of the likelihood of leakage it is preferable to make a special dive to maximum depth for the estimation of compression and to make it with as little delay as possible.

### 5.1.5 Measurements of Ballast Changes

The liquidometer gauges measuring the contents of the auxiliary ballast tanks are not very sensitive and may vary in their indication by as much as 500 pounds when no change has been made in the content of the tank. This is due in part to the effect of small changes in the angle at which the hull lies in the water.

To minimize this source of error all ballast changes during a test should be made in a single tank, so that the errors in reading several gauges are not added. If changes in fore and aft trim are required they should be made by pumping from one tank to another rather than to and from the sea.

The pump gauges installed in the earlier fleet-type submarines are very inaccurate. These gauges operate by counting the pump strokes. Leakage of the valves causes the delivery to fall below the indication. Pumps installed more recently appear to be more reliable and measure the water pumped more precisely than do the liquidometer gauges. These pumps, however, cannot be used to measure the amounts of ballast flooded.

So long as ballast adjustments were made entirely by trial, accurate measurements of ballast changes were not necessary. If full advantage is to be taken of the improvement in precision of operation, which is possible with instruments for predicting ballast changes, improvements in the design of tanks and gauges are needed.

## 5.2 THE COMPRESSION OF SUBMARINES

### 5.2.1 Results of Compression Tests

Fleet-type submarines have yielded values for compression varying from 500 to 8,000 pounds per hundred feet. Beginning with the SS 285 commissioned in the spring of 1943, important changes in hull construction were introduced with a view to increasing the depth of safe operation. Submarines of earlier design will be referred to as light-hulled, and subsequent construction as heavy-hulled vessels. Four submarines, SS 361-364, were modified only with regard to the weight of the frames, the plating being similar to that used in the earlier vessels. Table 2 shows the results of tests on 50 vessels, and is arranged to show the number of submarines of each type yielding various magnitudes of compression.

TABLE 2. Compression of Fleet-type Submarines.

| Type of vessel | Number of tests | Range of compression | | | | Average compression |
|---|---|---|---|---|---|---|
| | | <1,750 | 1,750-2,500 | 2,500-3,500 | 3,500 | |
| Light hull (SS 212–284) | 25 | 5 | 6 | 9 | 5 | 2,700 |
| Light hull—heavy frames (SS 361–364) | 4 | 1 | 3 | 0 | 0 | 2,000 |
| Heavy hull (SS 285 and SS 313 class) | 26 | 13 | 10 | 3 | 0 | 1,700 |

These tests make it clear that the compression varies with the hull construction. No differences were demonstrated between the products of different yards. Since the observations were made for the most part on new construction during deep-submergence tests it is probable that leakage and perhaps other causes, such as the inexperience of new crews, has led to undue variation in the results and on the whole to values which are too large. It is not probable that minor differences in design and construction are responsible for the extreme differences observed among submarines of the same class.

Information obtained at Pearl Harbor confirms the belief that tests with seasoned vessels and crews yield somewhat lower values for compression. The values for the compression of such vessels indicated by tests and patrol experience are given in Table 3.

Table 3. Compression of Seasoned Submarines.

| Type of vessel | Number of vessels | Compression lb per 100 ft |
|---|---|---|
| Light hull including | 2 | 1,500 |
| T and Gato class | 8 | 2,000–2,200 |
| | 2 | 2,500–2,800 |
| Average: | | 2,090 |
| Heavy hull Balao | 1 | 1,700–1,900 |
| class | 10 | 1,300–1,500 |
| Average: | | 1,430 |

Of the older types of submarine, controlled compression tests have only been made on the S-33 which yielded a value of 3,000 pounds per 100 feet. This vessel displaced 1,070 tons submerged. This compression corresponds to 6,700 pounds per 100 feet for a vessel of 2,400 tons.

Experience in diving has indicated that the compression of other old type submarines are about as given in Table 4.

Table 4. Compressions of Older Type Submarines.

| Class | Submerged displacement tons | Number of vessels reported | Compression lb per 100 ft | Corresponding compression for 2,400 tons |
|---|---|---|---|---|
| S (new) | 2,200 | 5 | 2,000–2,500 | 2,200–2,700 |
| P | 2,000 | 3 | 2,500–3,000 | 3,000–3,600 |
| S (old) | 1,100 | 5 | 1,100–2,700 | 2,400–3,400 |

Estimates have been made on the compression of four British submarines from data supplied by the British Admiralty delegation through courtesy of Captain (S) Third Submarine Flotilla, HMS Forth, and is recorded in Table 5.

Table 5. Compressions of British Submarines.

| Vessel | Submerged displacement tons | Compression lb per 100 ft | Corresponding compression for 2,400 tons |
|---|---|---|---|
| Venturer | 800 | 750 | 2,250 |
| Viking | 800 | 1,050 | 3,500 |
| Stratagem | 1,000 | 937 | 2,250 |
| Spirit | 1,000 | 900–1,000 | 2,160–2,400 |

These compressions agree in general with those reported for the older type of American submarines.

Taken as a whole, the data indicate that slight improvements in compressibility have been made with the development of the light-hulled fleet-type submarine. The new heavy-hulled fleet-type submarine is, however, distinctly improved in this respect.

### 5.2.2 Variation in Compression of Individual Submarines

The measurements of compression of fleet-type submarines summarized above show surprisingly wide variation. This variation is attributable in part to inaccuracies inherent in the method of making the tests and to faulty technique in carrying out the determination. The residue may result from real differences in the design and construction of the vessels and there is in addition the possibility that unrecognized factors are also contributory.

Data are available from 19 submarines on which the compression has been estimated during two or

Table 6. Selected Data on Compressibility of Submarines in Which Duplicate Tests Agree Within 500 Pounds per 100 Feet.

| Vessel | Mean compression | Variation |
|---|---|---|
| (Light hull) | | |
| Puffer* | 1,900 | ±300 |
| Pargo* | 3,150 | ±350 |
| Bluefish* | 3,300 | ±300 |
| Cod* | 2,900 | ±500 |
| Darter* | 3,300 | ±100 |
| Golet | 2,300 | ±100 |
| Cobia | 2,300 | ±300 |
| Class Average | 2,730 | |
| Average of extreme mean values | 2,600 | ±700 |
| (Heavy hull) | | |
| Cisco* | 1,550 | ±150 |
| Apogon* | 1,880 | ±500 |
| Aspro* | 2,250 | ±350 |
| Pintado* | 900 | ±100 |
| Dragonet | 1,300 | ±380 |
| Redfish | 1,450 | ±350 |
| Class Average | 1,540 | |
| Average of extreme mean values | 1,575 | ±675 |

* These check dives were made on same test cruise.

more separate dives. Thirteen of these, which show agreement on successive tests within ± 500 pounds of their mean, are recorded in Table 6. This agreement is as good as can be expected, considering errors in reading ballast tank liquidometer gauges and in securing trim at low speed. Measurements influenced by faulty technique in securing trim or otherwise handling the vessel are probably excluded.

Table 6 shows that the average compression of the selected light-hulled submarines is 2,730 pounds per 100 feet. The extreme values of mean compression for individual vessels fall within ± 700 pounds of their average of 2,600. For the heavy-hulled submarines the average compression is 1,540 pounds per 100 feet. The extreme values of mean compression for individual vessels fall within ± 675 pounds of their average of 1,575.

The result confirms the conclusion that a real difference exists between the compression of submarines of different design and construction. The variation between different vessels of the same class is large enough to suggest that there may be some real difference in their compressibility, but a larger series of measurements is required to demonstrate this point.

### 5.2.3 The True Compressibility of Submarine Hulls

Compression tests measure the combined effects of hydrostatic pressure on the displacement of the hull and on the density of the displaced sea water. Since the compressibility of sea water is known and increases the buoyancy of a submerged submarine of 2,400 tons displacement by about 500 pounds per 100 feet, it is necessary only to add this amount to the measured compression to obtain an indication of the actual change in displacement of the submarine.

Thus one of the older light-hulled type submarines with a measured compression of 2,700 pounds per 100 feet actually undergoes a change in displacement of about 3,200 pounds and a modern heavy-hulled vessel with a compression of 1,400 pounds displaces about 1,900 pounds less on descending 100 feet. Improvements in design have almost doubled the rigidity of submarine hulls. Further improvements in like degree would reduce the true hull compression until it is nearly equal to the compressibility of sea water. If this could be accomplished submarines would never need to pump ballast on descent, and whenever density gradients were present they could float balanced in the gradient without depending on propulsive machinery to maintain their proper depth.

Improvements in design intended to permit greater range in depth and improved resistance to depth charges may thus also increase the ease of underwater operation.

### 5.2.4 Batten Measurements

A direct indication of the effect of compression with depth on the displacement of a submarine's hull is given by measurements of the change in diameter of the pressure hull on deep submergence. These measurements, made with steel battens secured to brackets welded to the pressure hull frames, are customarily made in both the vertical and horizontal direction in the seven compartments of the hull during precommissioning trials.

Data secured by the Supervisor of Shipbuilding, U.S.N., at Manitowoc, Wisconsin, during deep-submergence tests of 22 submarines of new construction, indicate that the average decrease in diameter of the pressure hull is 0.0295 inch per 100 feet descent in the case of light-hulled vessels and 0.0275 inch per 100 feet descent in the case of the heavy-hulled submarines of later design. These changes in diameter are estimated to lead to a decrease in displacement of 1,650 and 1,540 pounds per 100 feet respectively.

These estimates of the true compressibility of the submarine hulls are notably lower than those based on ballast changes required during deep submergence, which are 3,200 and 1,900 pounds per 100 feet respectively for the two types of construction. The difference may be attributed in part to the compression of fuel oil and entrapped air since these factors lead to excessive values in the compression tests. More important, the batten measurements do not record the bending of the plates between frames, and consequently give too small a value for the change in displacement of the pressure hull.

## 5.3 EFFECT OF ENTRAPPED AIR ON APPARENT COMPRESSION

Any large volume of air entrapped in a fuel or ballast tank or in any other place where it is exposed to the pressure of the sea will be compressed when the submarine descends and will cause an undue loss of buoyancy. If such a condition exists during a compression test, abnormally high values for compression will result. It is believed that when compression measurements yield results more than 1,000 pounds in excess of the mean value for boats of the class, air is present. It is suspected that smaller departures from the mean compression may frequently be due to the accidental entrapment of smaller quantities of air.

In the construction of a submarine, every effort is made to eliminate air pockets and, if vent holes are cut in accordance with the detailed working plans, there should be a negligible amount of air trapped in the tanks or in the outside structure. However, it sometimes happens that sections of the superstructure are not adequately provided with vent holes during construction and these pockets are uncovered in service if the volume is sizable enough to cause erratic performance in diving. In the absence of pockets of this type, there is always the possibility that the tanks are not properly vented to eliminate all the air possible.

The presence of entrapped air reveals itself in the way in which buoyancy decreases with depth. Normally, as the result of compression, the volume displacement of the vessel decreases in direct proportion to the depth. On the other hand, since pressure increases with depth, the volume displacement of an entrapped air bubble is the reciprocal of the depth, since the volume of a gas is inversely proportional to its pressure. As a result, the net buoyancy of a vessel carrying a large volume of entrapped air decreases very rapidly at the beginning of its descent but less and less rapidly as depth increases. The estimated compression of the vessel, which represents the sum of the true compression[d] and the compression of the air bubble, will consequently diminish when measured between successively deeper levels.

A bubble having a volume at sea level equal to the displacement of 1,000 pounds of sea water[e] has an effect on the buoyancy of a submarine at any keel depth which is given by the term $\dfrac{1{,}000}{1 + \dfrac{D\text{-}15}{33}}$ pounds, where $D$ is the keel depth in feet, it being assumed that the bubble is centered 15 feet above the keel. The form of this relation is illustrated in Figure 1. It is evident from this figure that the greater part of the loss of buoyancy from the compression of the air will occur between the surface and 100 feet depth and that below 200 feet the effect of further compression of the air is relatively small.

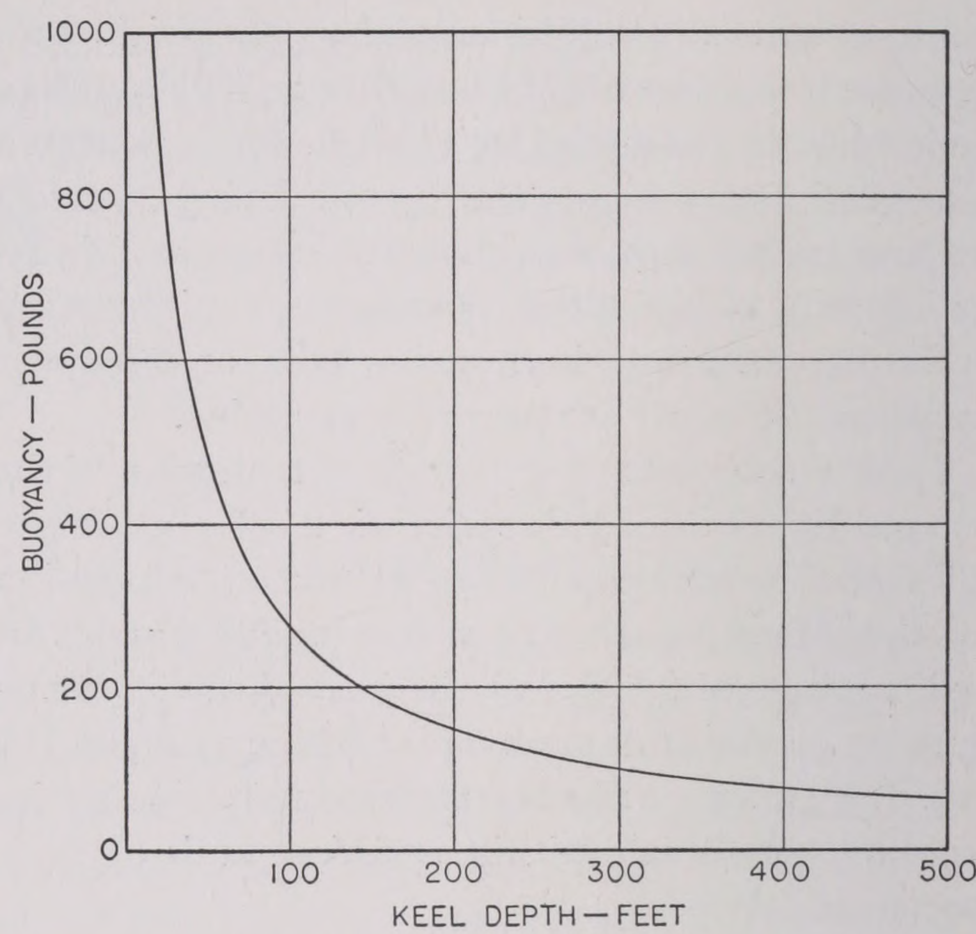


FIGURE 1. Effect of a volume of entrapped air, which at atmospheric pressure displaces 1,000 lb of sea water, on the buoyancy of a submarine at various keel depths.

The size of an entrapped air bubble may be determined approximately with the aid of Figure 1 if hydrographic conditions and the compression of the submarine are known or may be reasonably assumed. If the displacements of a quantity of air which displaces 1,000 pounds of sea water at the surface are represented by $V_1$ and $V_2$ at the depth $Z_1$ and at some greater depth $Z_2$, then the displacement at the surface is given by[f]

$$\frac{\Delta W - C(Z_2 - Z_1)/100 - V\Delta \rho_{ts}}{V_2 - V_1} \times 1{,}000 \text{ pounds,} \tag{1}$$

and the volume of gas at 1 atmosphere pressure is given by

$$\frac{\Delta W - C(Z_2 - Z_1)/100 - V\Delta \rho_{ts}}{V_2 - V_1} \times 15.6 \text{ cu ft.} \tag{2}$$

[d] The true compression here refers to the combined effect of compression of the hull and compression of sea water.

[e] 1,000 pounds of water are displaced by 15.6 cubic feet or 118 gallons.

[f] In these expressions in accordance with definitions previously given $\Delta W$ = change in ballast between depths $Z_1$ and $Z_2$; $C$ = change in buoyancy due to compression per 100 feet increase in depth; $V$ = submerged displacement of submarine in pounds; $\Delta\rho_{ts}$ = change in density of sea water between depths $Z_1$ and $Z_2$.

The pressure and size of an unsuspected bubble of entrapped air is indicated by the data in Table 7 secured during a dive of a British submarine of 1,000 tons displacement. The first part of the table shows the data obtained at several levels between 30 and 300 feet from which the compression is estimated between each descending pair of levels. The apparent compression represents the change in buoyancy of the vessel due to compression in descending from 30 feet to the stated depth, estimated from the ballast change and the change in density of the sea water. The estimated compression shows the compression per 100 feet between each stated depth. It is evident that the compression is much greater at the upper levels than between deeper levels, which indicates that entrapped air is present. In the second part of the table, the displacement of the air is estimated from the change in buoyancy between 30 feet and each greater depth. This is done by estimating the change in buoyancy due to the actual compression of the hull, assuming a reasonable value (−1,100 pounds per 100 feet) for the buoyancy due to compression (column 3). The difference between change due to the apparent compression and the assumed compression, gives the change in buoyancy due to the assumed air bubble (column 4). The change in buoyancy of a 1,000-pound air bubble at each stated depth is then obtained from Figure 1 and entered in column 5. By comparing the change in buoyancy of the assumed air bubble and the 1,000-pound air bubble, the displacement of the air is obtained (column 6). The results indicate that the air displaces about 7,000 pounds corresponding to 109 cubic feet when at the surface.

TABLE 7. Apparent Compression of the 1,000-ton Submarine, HMS SPIRIT Suspected of Carrying Entrapped air.

| | Change in buoyancy due to | | | |
|---|---|---|---|---|
| Depth | Change in ballast | Density of sea water | Apparent compression | Estimated compression lb/100 ft |
| 30 | 0 | 0 | 0 | — |
| 100 | −1,250 | +2,240 | −3,490 | 4,986 |
| 200 | −2,500 | +3,360 | −5,860 | 2,370 |
| 300 | −3,400 | +3,360 | −6,760 | 900 |

Estimation of Displacement of Air Assuming Compression of −1,100 Pounds per 100 Feet.

| | Change in buoyancy due to | | | | |
|---|---|---|---|---|---|
| Depth | Apparent compression | Assumed compression | Assumed air bubble | 1,000-pound air bubble | Estimated displacement of air |
| 30 | 0 | 0 | 0 | 0 | — |
| 100 | −3,490 | −770 | −2,720 | −400 | 6,800 |
| 200 | −5,860 | −1,870 | −3,990 | −530 | 7,528 |
| 300 | −6,760 | −2,970 | −3,810 | −580 | 6,570 |

In this case, the compression of the submarine was unknown. The apparent compression between 200 and 300 feet suggested the proper order of magnitude and trials were made with various compressions until the most uniform values for the displacement of the air were obtained. This is obviously not a satisfactory method of determining compression. When the results of compression tests indicate the presence of entrapped air, the condition should be remedied and the test repeated under more favorable circumstances.

Definite evidence of the effects of entrapped air were obtained during the deep-submergence test of the USS FLOUNDER. Immediately prior to the test a trim dive was made in order to weigh the vessel. From the ballast adjustments required to trim the submerged vessel, it was estimated that a large amount of air was present in one of the after fuel tanks. The size of this bubble was estimated to be 700 to 800 cubic feet at periscope depth, corresponding to 1,800 to 2,000 cubic feet at the surface.

TABLE 8. Apparent Compression of the 2,400-ton Submarine USS FLOUNDER (SS 251) Carrying Entrapped Air.

| | Change in buoyancy due to | | | |
|---|---|---|---|---|
| Depth | Change in ballast | Density of sea water | Apparent compression | Estimated compression lb/100 ft |
| 90 | 0 | 0 | 0 | — |
| 162 | −9,500 | +50 | −9,500 | 13,200 |
| 212 | −12,800 | +320 | −13,120 | 7,240 |
| 312 | −13,400 | +4,260 | −17,660 | 4,540 |

Estimated Displacement of Air Assuming Compression of 2,600 Pounds Characteristic of Class.

| | Change in buoyancy due to | | | | |
|---|---|---|---|---|---|
| Depth | Apparent compression | Assumed compression | Compression of air | 1,000-pound air bubble | Estimated displacement of air |
| 90 | 0 | 0 | 0 | 0 | — |
| 162 | −9,500 | −1,870 | −7,630 | −120 | 63,600 |
| 212 | −13,120 | −3,170 | −9,950 | −155 | 64,110 |
| 312 | −17,660 | −5,770 | −11,890 | −185 | 64,400 |

Following the trim dive, the FLOUNDER made a deep-submergence test in the course of which the data recorded in Table 8 were secured, and the displacement of the entrapped air estimated as explained in discussing the data obtained by the HMS SPIRIT.

The change in ballast required to compensate for compression was unusually large and the estimated compression is much greater between levels near the surface than between deeper levels. When the displacement of the air is estimated, assuming a compression for the FLOUNDER of −2,600 pounds per 100 feet, which is the average value for her class, a value of about 64,000 pounds or 1,000 cubic feet at one atmosphere pressure was obtained.

On return to the yard, Number 6A and 6B Fuel Tanks were found to be only about one-quarter full, verifying the existence of an air bubble. From the content of the tank, it was estimated that the volume of air was about 900 cubic feet. Comparing the results of the three methods of estimation, the volume of air was as follows:

| | |
|---|---|
| Weighing boat . . . . | 1,800 to 2,000 cubic feet |
| Compression test . . . . . . . . | 1,000 cubic feet |
| Direct observation . . . . . . . . | 900 cubic feet |

The location of the entrapped air should be indicated approximately from the change in fore and aft trim required on descent if the displacement of the air is known. If the air is entrapped at some distance aft of the center of buoyancy, for example, its compression will cause the submarine to become heavy aft and an appropriate amount of ballast must be tranferred forward to compensate. The quantity of ballast shifted will depend on the change in displacement of the air and the ratio of the distances of the bubble and of the fore and aft tanks from the center of buoyancy.

The approximate position of the entrapped air should be indicated by $L$ in the equation:

$$L = \frac{d_A \triangle W_A - d_F \triangle W_F}{\triangle D}. \tag{3}$$

where $L$ = distance measured *aft* of center of buoyancy;

$d_F$ = distance of forward trim tank from center of buoyancy;

$d_A$ = distance of aft trim tank from center of buoyancy, and where between any two depths;

$\triangle W_F$ = change in ballast in forward trim tank;

$\triangle W_A$ = change in ballast in aft trim tank;

$\triangle D$ = change in displacement of entrapped air.

A negative value of $L$ indicates air entrapped forward of the center of buoyancy.

In the case of the observations on the USS FLOUNDER on descending from 90 feet to 312 feet:

$$\triangle W_F = +900 \text{ pounds}$$

$$\triangle W_A = -5{,}500 \text{ pounds}$$

$$\triangle D = -11{,}890 \text{ pounds}$$

$$d_F = 120 \text{ feet}$$

$$d_A = 140 \text{ feet}$$

The distance of the air aft of the center of buoyancy, $L$, comes out to be 73.8 feet. Tanks 6A and 6B, in which the air was located, center 44 feet aft of the center of buoyancy. The agreement is not very satisfactory and indicates that the position of the bubble can be determined only in a very general way by such estimations.

Submarines are sensitive to small changes in fore and aft trim since a change of only 200 pounds causes a change in hull angle of 1 degree. Whenever a submarine becomes unexpectedly heavy at one end on changing depth the possible presence of entrapped air should be considered.

## Chapter 6

# THE PREDICTION OF BUOYANCY CHANGES DUE TO DENSITY GRADIENTS IN THE SEA

MEASUREMENTS of density of sea water obtained by the use of hydrometers or by chemical analyses for salinity and from temperature readings take too long to be a useful guide to actual diving operations. A continuous and instantaneous indication of the density of sea water, preferably in the form of a graphic record of its effect on buoyancy with changing depth, is needed to provide useful information to the diving officer as the vessel moves from one depth to another.

### 6.1 SUBMARINE BATHYTHERMOGRAPH

The type CTB submarine *bathythermograph* [BT],[a] an instrument designed originally for use in sonar predictions, provides this information in so far as density gradients due to temperature differences in the water are concerned. Since temperature differences are the principal source of density layers in most parts of the ocean, this instrument has proved of immediate value as a guide to diving operations. The OCN and OCO are more recently developed temperature-depth recorders intended to improve on the type CTB bathythermograph in various ways. The model CXJC is an instrument which takes account of density effects due to salinity as well as temperature.

The type CTB submarine bathythermograph draws a curve on a smoked card as the submarine dives. The principle of operation is evident from Figure 1. The card carriage is rotated about a pivot by a Bourdon tube actuated by the sea pressure. The upward movement of the card holder during descent causes the

[a] Abbreviation for bathythermograph. See note a, Chapter 1.

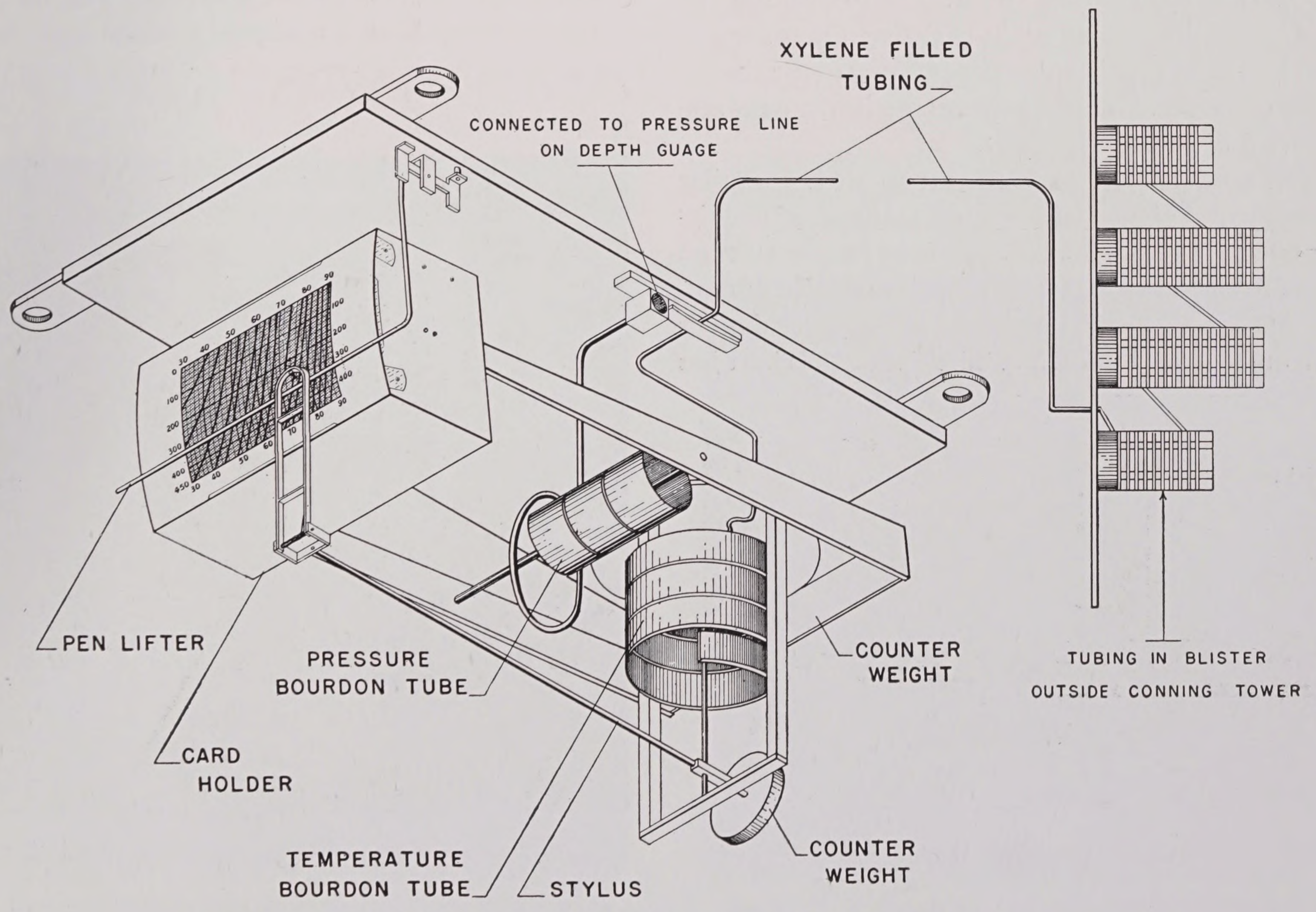


FIGURE 1. Diagram showing principles of construction of Type CTB bathythermograph.

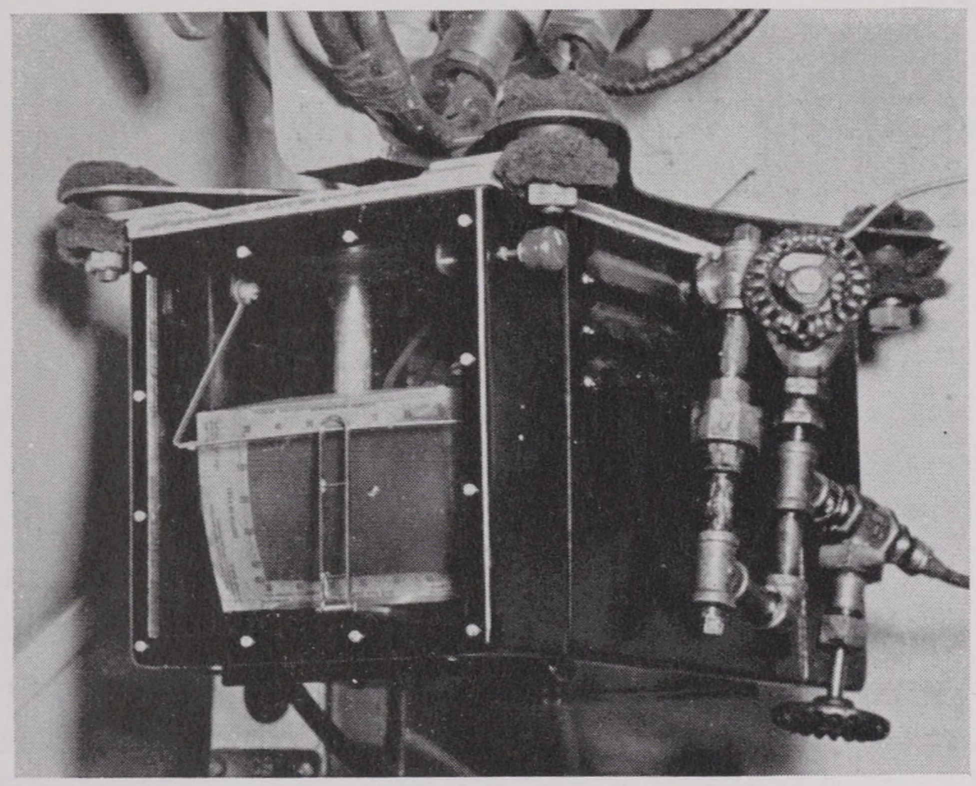

FIGURE 2. Type CTB bathythermograph installed.

writing point to trace a descending line on the smoked card, proportional in length to the increase in depth. The writing point is mounted on an arm which rotates in a horizontal plane under the action of a second Bourdon tube connected with a temperature sensitive element exposed to the sea, usually at the level of the conning tower. The rotation of the arm causes the writing point to deflect the tracing to the right or left, a distance proportional to the change in temperature. Figure 2 pictures the instrument and Figure 3 illustrates the chart.

The model OCN bathythermograph is a similar instrument designed with the special needs of the diving officer in mind. The shape of the instrument has been modified to provide for more convenient mounting on the panel carrying the depth gauges and other instruments used in diving. The size of the chart has been increased so that the record can be read by the diving officer while standing at his station. These changes have involved complete redesign of the mechanical arrangements, but in principle it differs in no way from the CTB model. The model OCN bathythermograph is pictured in Figures 4 and 5 and the chart is shown in Figure 6. The model OCN is now receiving test in service.

The model OCO bathythermograph, like the models CTB and OCN, also records temperature and depth but employs electrical methods of recording. Temperature is measured by a thermocouple which generates a voltage in an electrical circuit. This voltage is measured by means of a potentiometer circuit in the recorder, located in the control room, and is plotted on the vertical scale of the recorder in degrees of temperature. Depth is measured by sea pressure acting on a bellows connected with a slide-wire which is one arm of a Wheatstone bridge, the other arm of the bridge being in the recorder. Depth is plotted on the horizontal scale in the recorder. The depth-temperature curve is written in ink on a chart which is 7x10 inches in dimensions. There are three separate thermocouples which are installed at the bow, on the periscope shears, and just above the bilge keel. Any one of these thermocouples can be thrown into the

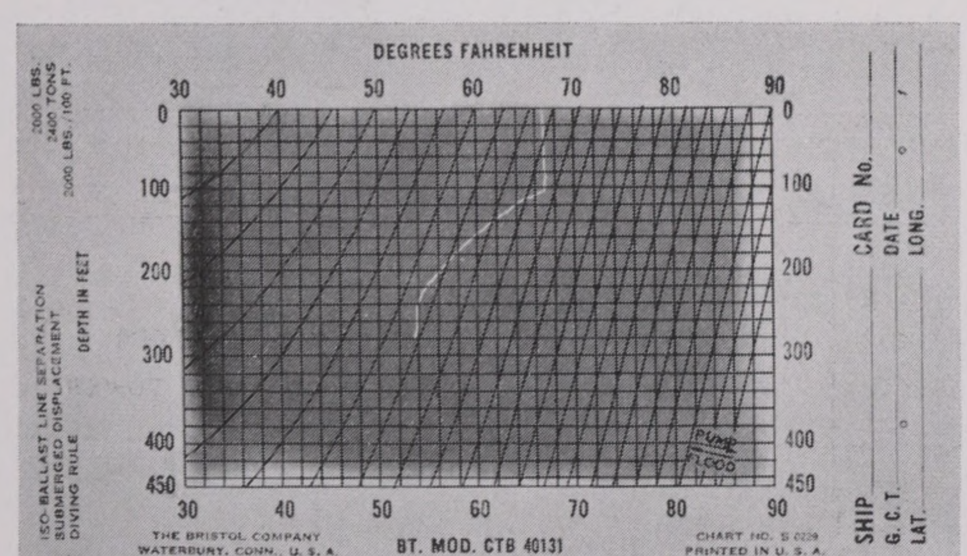


FIGURE 3. Smoked chart used in type CTB bathythermograph, showing simulated temperature trace. Reduced to 3/5 natural size.

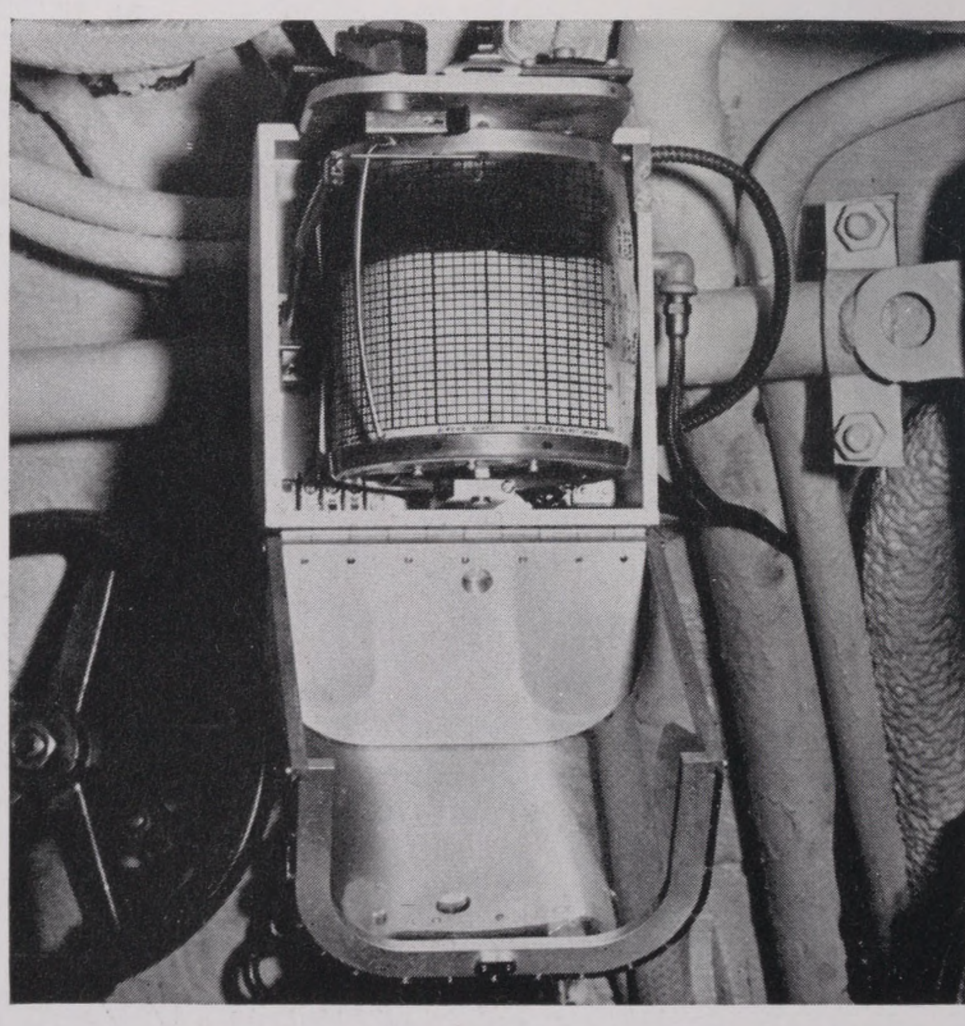

FIGURE 4. Model OCN bathythermograph installed in the control room. The cover has been opened and smoke removed from lower portion of the card to show the chart more clearly.

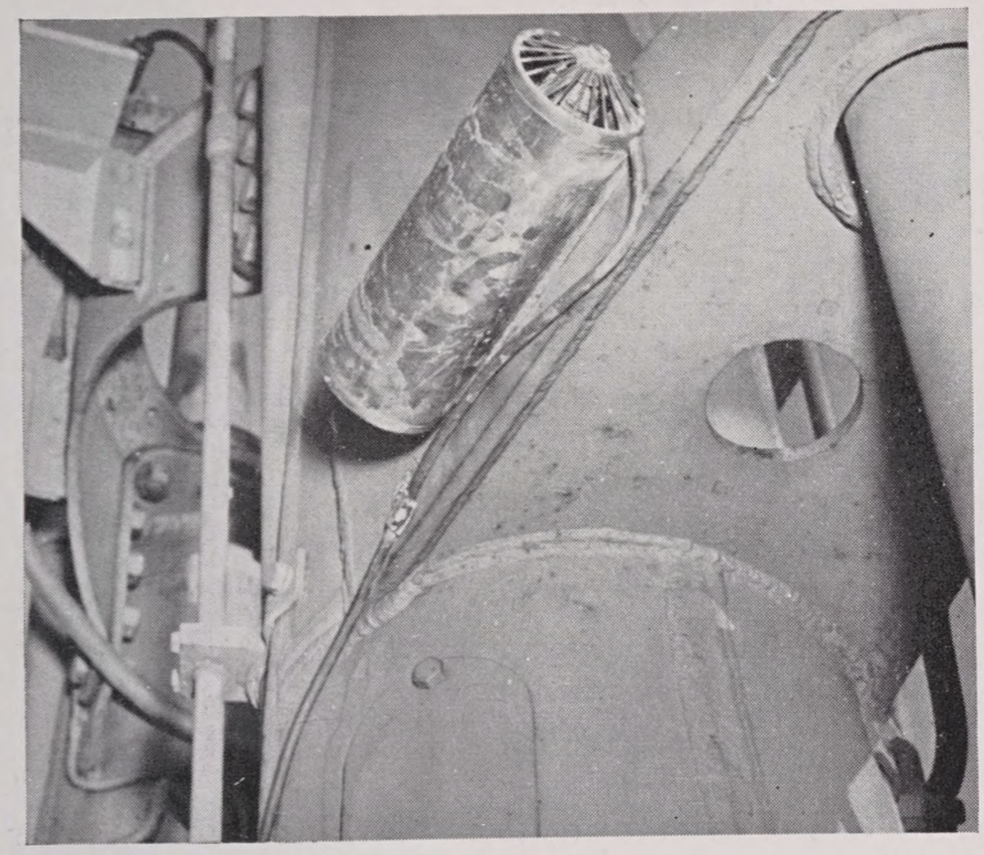

FIGURE 5. Temperature-sensitive element of model OCN bathythermograph installed on the periscope shears.

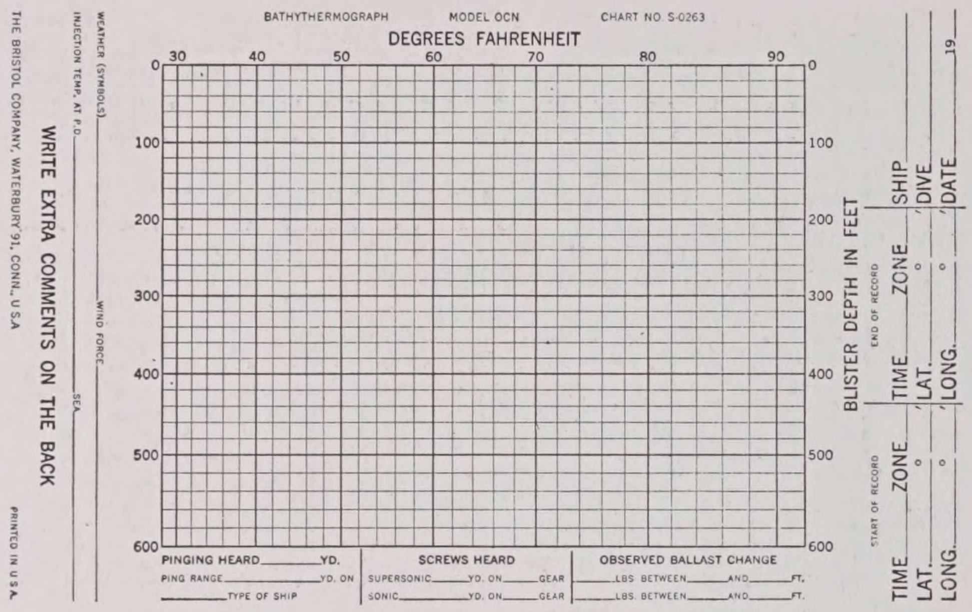


FIGURE 6. Chart used in model OCN bathythermograph. Reduced to 2/5 natural size.

circuit by means of a switch on the recorder. The OCO recorder is shown in Figure 7, and the thermocouple in Figure 8.

## 6.1.1 The Interpretation of the Bathythermograph Record

The tracing drawn by the instrument is a description of the distribution of temperature with depth. In order to make use of this information in estimating the ballast adjustment required on changing depth, it is necessary to provide some means of showing the change in buoyancy which will result from the change in temperature. It is also necessary at the same time to take account of the change in buoyancy which results from the compression due to increasing depth.

This is done by adding to the bathythermograph chart a third set of coordinates which are sloped so that each passes through all the points where the loss in buoyancy with depth from compression is exactly equal to the gain in buoyancy due to a decrease in temperature. If the temperature of the water varies with depth as shown by such a line then no change in ballast is required on changing depth. Such lines are consequently called *isoballast* lines.

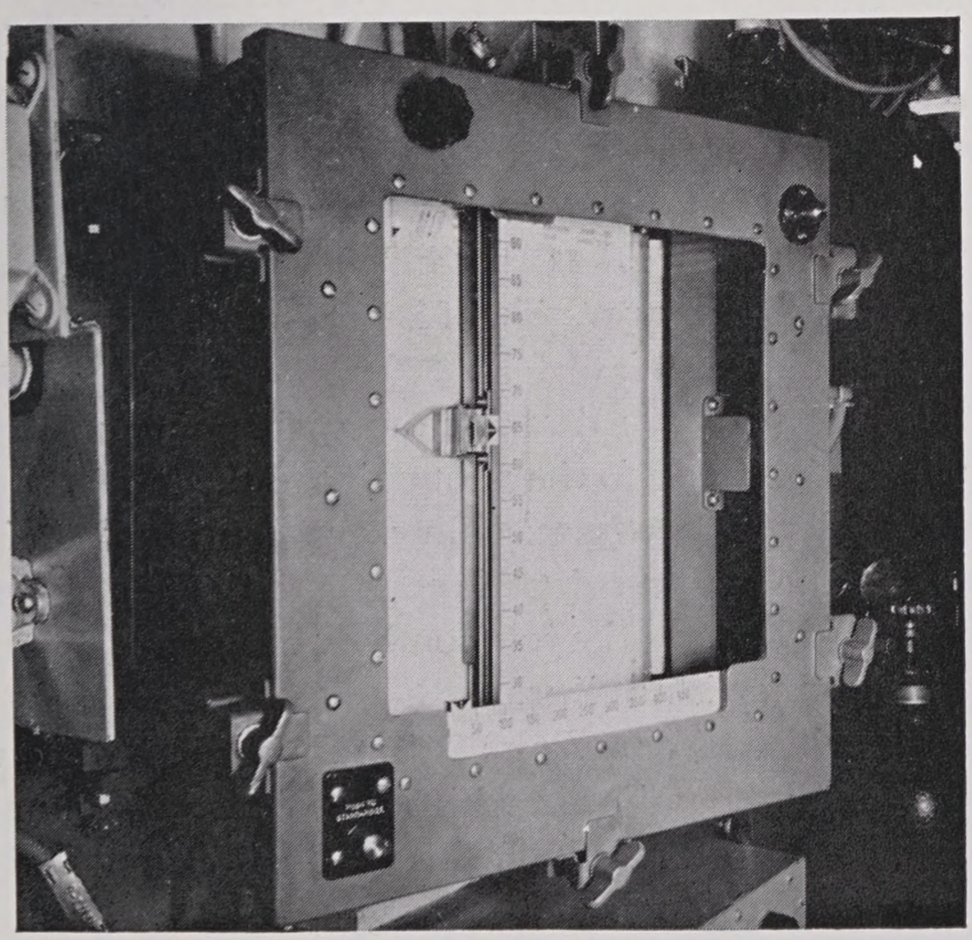

FIGURE 7. Model OCO bathythermograph installed in the control room.

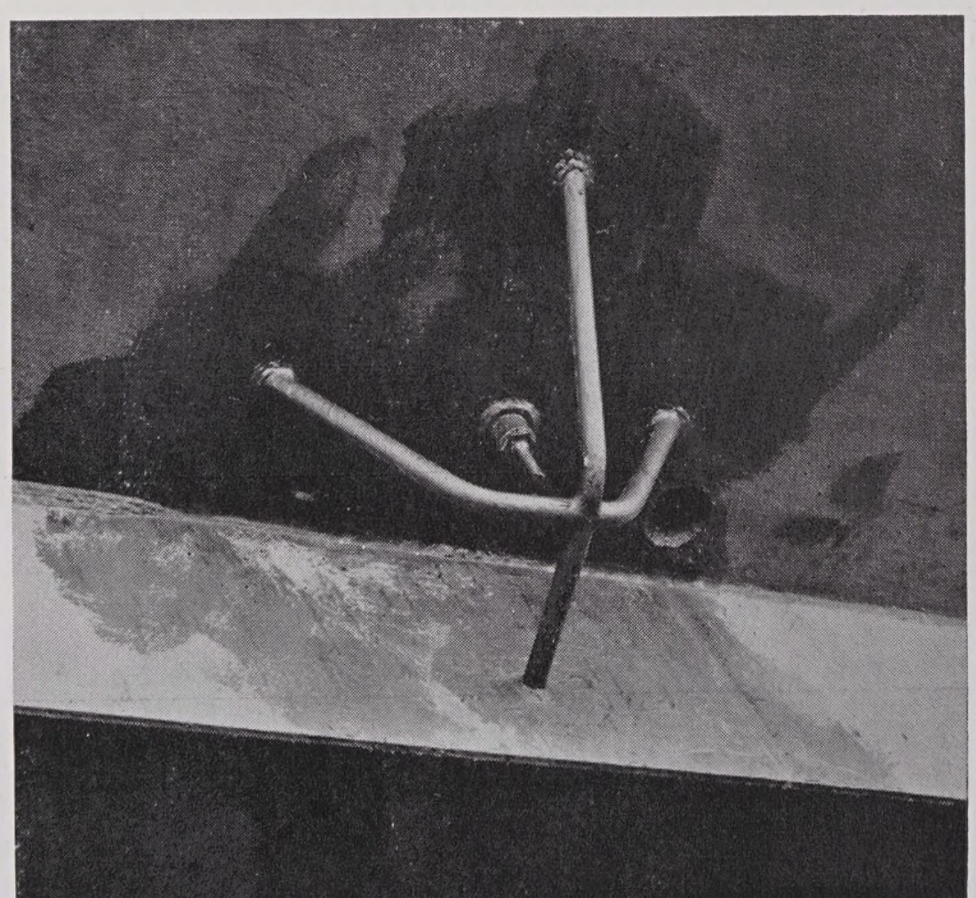

FIGURE 8. Thermocouple of the Model OCO bathythermograph installed at the level of the bilge keel.

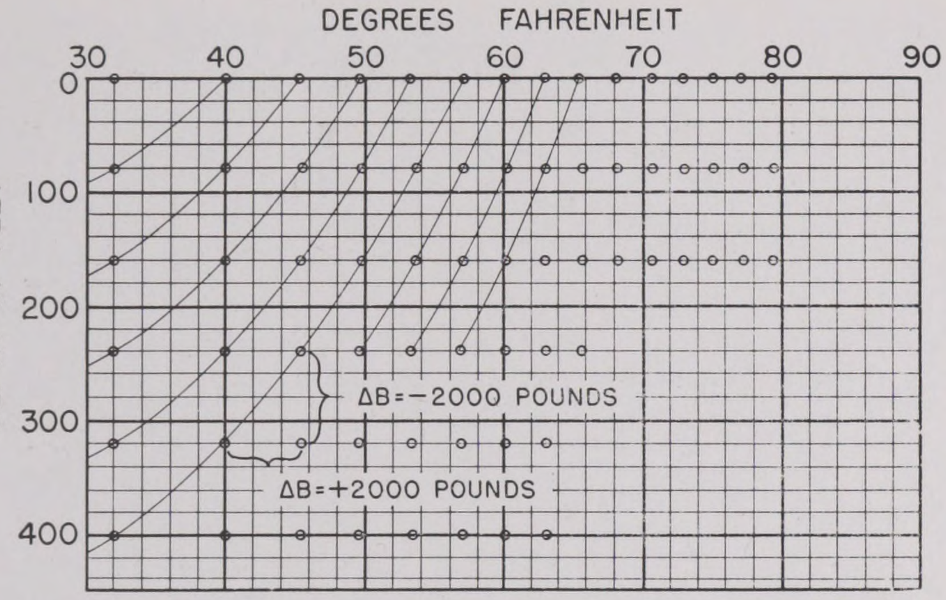


FIGURE 9. Method of constructing grid of isoballast lines on a bathythermograph chart. The example is for a submarine with compression of 2,500 lb per hundred feet.

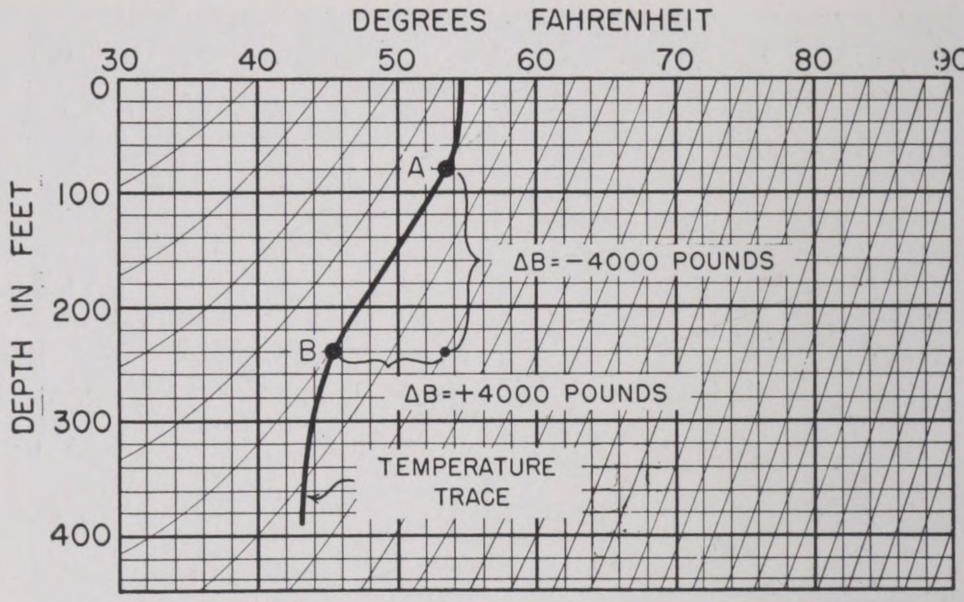


FIGURE 10. Example of temperature trace which follows an isoballast line, in which case no change in buoyancy occurs on changing depth.

The isoballast lines are spaced so that the interval between successive lines corresponds to a change in buoyancy of some fixed amount, conveniently 2,000 pounds. It follows that when the temperature trace crosses the isoballast lines between any two depths, the change in buoyancy is given directly by the number of isoballast-line intervals crossed. The ballast change required to compensate for the change in buoyancy may consequently be read off directly from the record.

The method of constructing isoballast lines will make this clearer. From a curve such as Figure 1 in Chapter 1, showing the relation between temperature and the relative buoyancy of a submarine, a table is constructed giving a series of temperatures each of which corresponds to a buoyancy 2,000 pounds less than the preceding. Such a series, appropriate to a submarine of 2,400 tons submerged displacement, is entered in Table 1.

TABLE 1. A Series of Temperatures for Use in Plotting Isoballast Lines for Submarines of 2,400 Tons Submerged Displacement.

Each increment in temperature corresponds to a change in buoyancy of 2,000 pounds.

| | | | |
|---|---|---|---|
| 32.0 | 56.9 | 70.5 | 81.5 |
| 40.0 | 59.9 | 72.8 | 83.7 |
| 45.3 | 62.8 | 75.0 | 85.8 |
| 49.6 | 65.6 | 77.2 | 87.9 |
| 53.2 | 68.1 | 79.4 | 90.0 |

The interval of depth which causes the buoyancy of the submarine to change by 2,000 pounds is next estimated from the relation:

$$\text{Depth interval} = \frac{2{,}000}{C} \text{ x } 100 \text{ feet}$$

where $C$ is the compression of the submarine for which the chart is intended. The depth intervals for various compressions for which isoballast lines have been issued are as follows:

| Compression (lb per 100 ft) | Depth intervals (ft) |
|---|---|
| 1,400 | 143 |
| 2,000 | 100 |
| 2,500 | 80 |
| 3,000 | 66.6 |
| 4,000 | 50 |

The temperatures corresponding to 2,000-pound increments in buoyancy, from Table 1, are marked off on the chart along the coordinate corresponding to the surface and again at the successive intervals of depth which each correspond to a 2,000-pound increment in buoyancy, as determined by the compression of the submarine for which the chart is intended. Figure 9 illustrates the procedure in the case of a submarine with a compression of 2,500 pounds for which the depth interval is 80 feet.

Sloping lines are drawn from each point on the surface coordinate to the next point to the left on the marked depth coordinate below, and continued similarly to the greatest depth represented. These lines are curved because the relation between temperature and buoyancy is not linear.

It is evident from Figure 9 that each line is drawn through all the points in which the decrease in buoyancy due to compression with depth is exactly balanced by the increase in buoyancy due to the decrease in temperature. Each line thus represents the conditions in which no change in ballast is required.

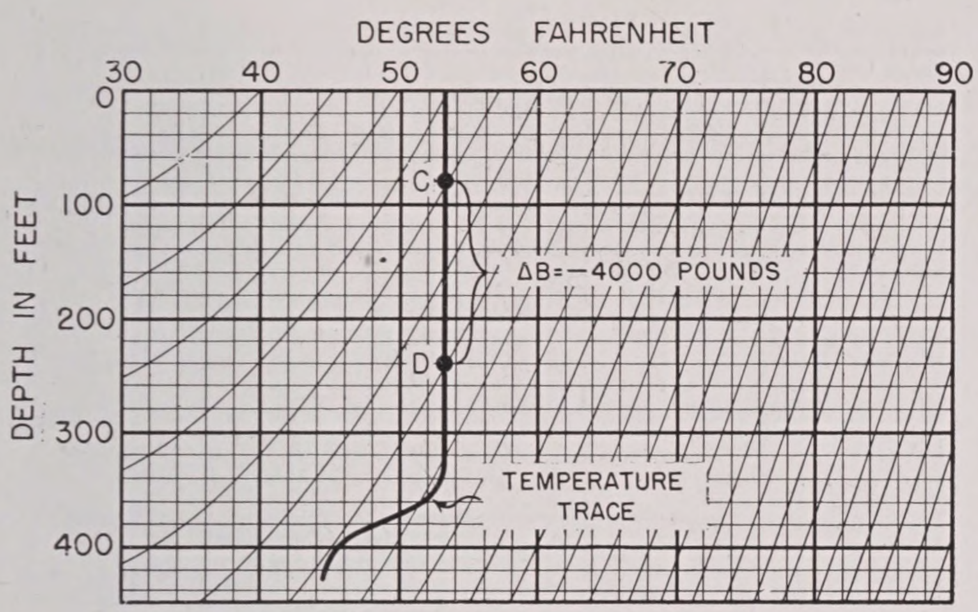


FIGURE 11. Example of temperature trace which crosses the isoballast lines from left to right on descent, in which case buoyancy decreases on increasing depth.

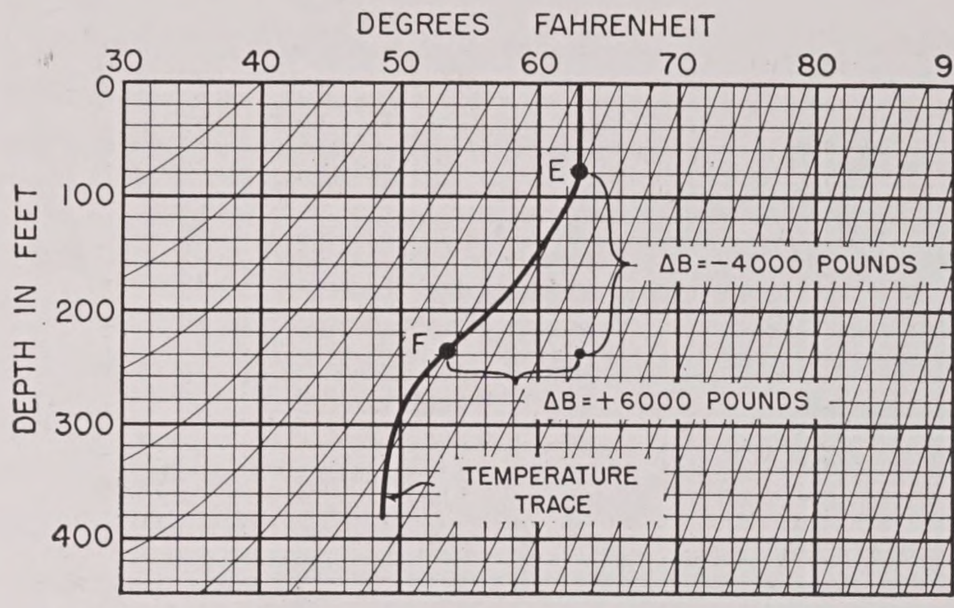


FIGURE 12. Example of temperature trace which crosses isoballast lines from right to left in descent, in which case buoyancy increases on increasing depth.

Thus if the temperature trace passes through the points A and B in Figure 10, a submarine in trim at A will lose 4,000 pounds buoyancy as the result of its compression in descending to B but will gain 4,000 pounds buoyancy as the result of the decreased temperature of the displaced water at B. No change in ballast is required.

It is also evident that if the temperature trace does not follow (or parallel) an isoballast line as in Figures 11 and 12, the buoyancy of the vessel will change on descent to a degree which is indicated by the isoballast line grid. Thus if the temperature does not change in descent, as from C to D in Figure 11, buoyancy is decreased 4,000 pounds because of compression. This is indicated by the tracing crossing two isoballast-line intervals. On the other hand, if the temperature decreases markedly on descent as from E to F in Figure 12, buoyancy is increased 6,000 pounds as the result of the temperature change while it is decreased 4,000 pounds by the compression. The result is an increase in net buoyancy of 2,000 pounds which is indicated directly by the fact that point F lies one isoballast-line interval to the left of point E. Consequently 2,000 pounds of ballast must be flooded in to preserve the trim which existed at E.

The following rules are sufficient to interpret the BT chart in making trim adjustments in diving.

1. If the temperature tracing crosses the isoballast lines from left to right during descent, the boat becomes heavier and ballast must be pumped out to obtain good trim. On ascent, it must be flooded in.
2. If it crosses the isoballast lines from right to left during descent, ballast must be flooded in to obtain good trim. On ascent, it must be pumped out.
3. If it is parallel to the isoballast lines, no change in ballast is required in moving from one depth to another.
4. The ballast change required in moving between two depths is given by multiplying the number of isoballast-line intervals crossed by the temperature tracing between these depths by 2,000 pounds. However, intervals crossed twice in opposite directions are not counted.

### 6.1.2 Graphical Analysis of Buoyancy Problems

The BT chart with isoballast lines provides a convenient means for the graphical analysis of buoyancy problems. It is consequently desirable to relate the fundamental buoyancy equations outlined in Chapter 3 to their graphical representation on the BT chart.

Equation (4) (Section 3.2) for change in net buoyancy, $\Delta B$, is:

$$\Delta B = V\Delta\rho_{ts} + C\Delta Z - \Delta W.$$

Since the instrument does not take account of salinity changes, the term $V\Delta\rho_t$ is used in place of $V\Delta\rho_{ts}$ to express buoyancy effects due to the temperature changes of the sea water. The terms of the equation may be expressed graphically by horizontal distances across the chart as shown in Figure 13. Their magnitude is measured in units of 2,000 pounds by the number of isoballast-line intervals crossed in the given distance. Thus if a submarine in trim at point A (depth $Z_1$ and temperature $T_1$) descends to point B (depth $Z_2$ and temperature $T_2$) and if D is the point at depth $Z_2$ on the isoballast line which passes

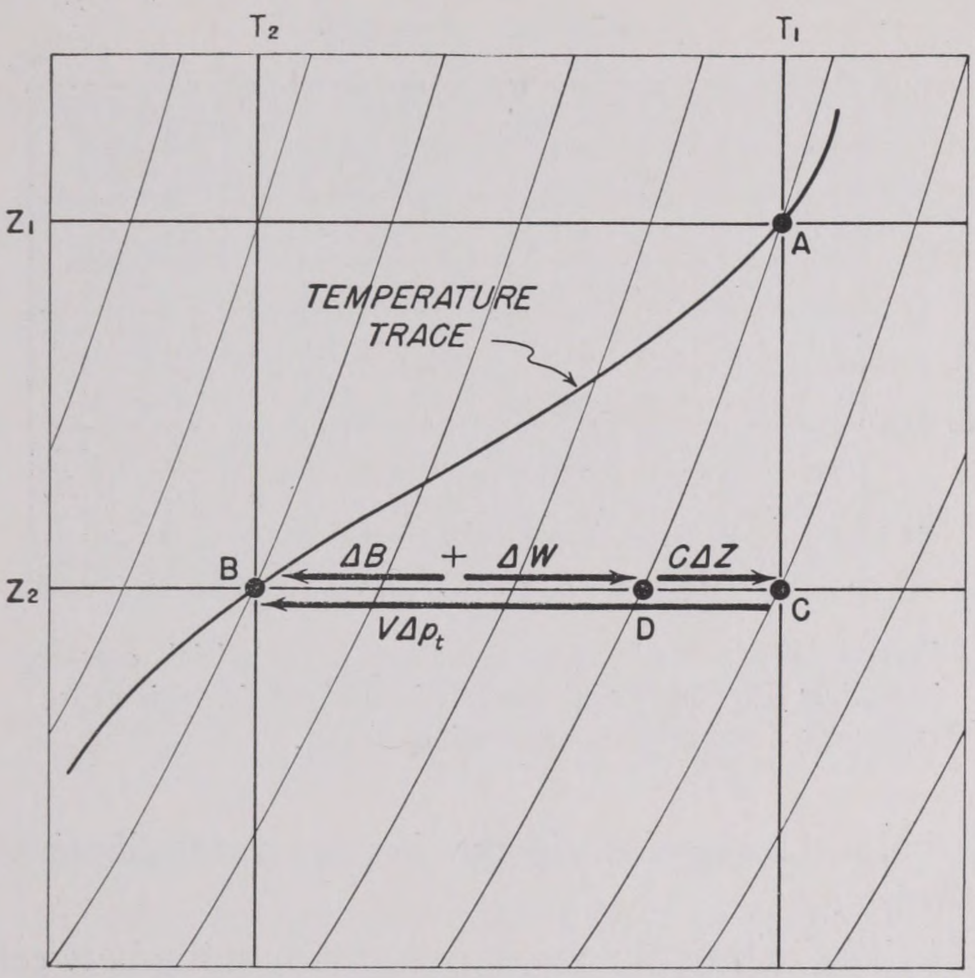


FIGURE 13. Graphical representation of factors affecting buoyancy with the aid of temperature trace drawn on isoballast line grid.

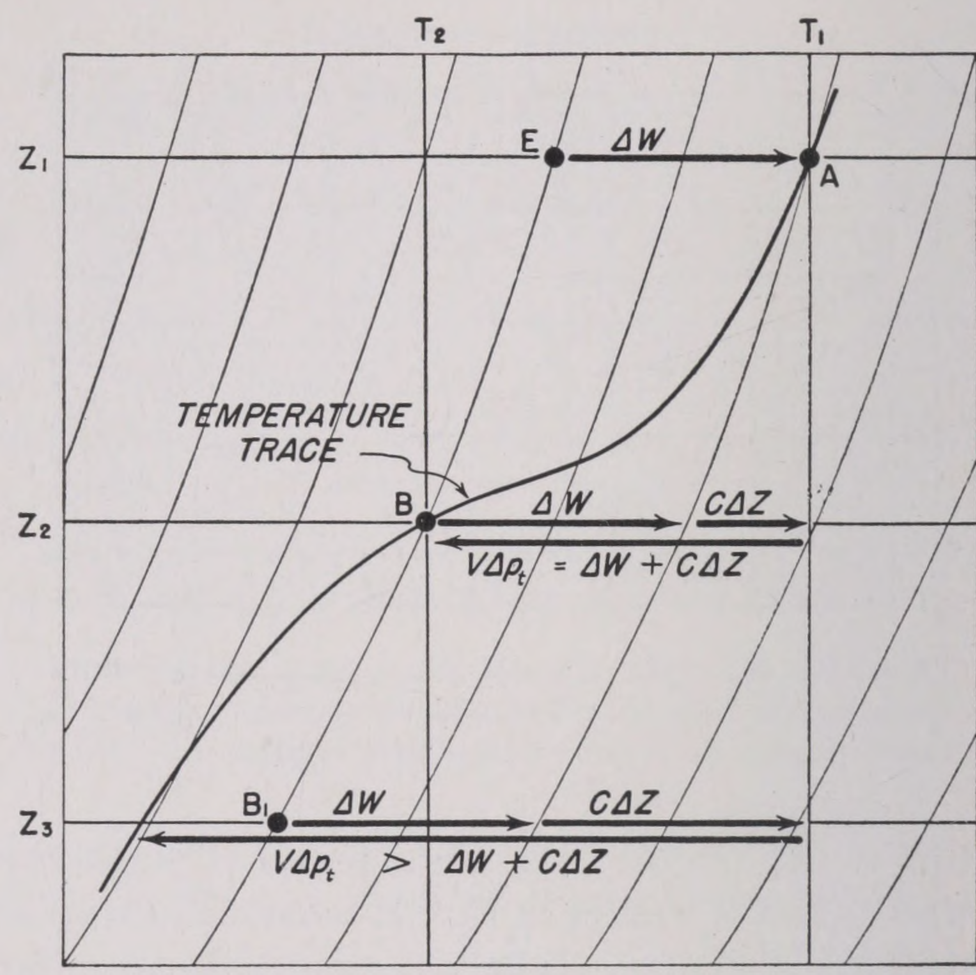


FIGURE 14. Use of graphical method to determine depth at which a submarine may come to trim when ballast is flooded in.

through the point of trim A, then $V\Delta\rho_t$ is represented by the distance CB which corresponds to the decrease in temperature, and $C\Delta Z$ is represented by the distance DC which corresponds to the temperature change required to counterbalance the compression. This is the result of the way in which the isoballast lines are constructed. $C\Delta Z$ has a negative value since it represents a *loss* in buoyancy.

The distance BD, equal to $V\Delta\rho_t + C\Delta Z$, represents the sum $\Delta B + \Delta W$. If $\Delta W = 0$, i.e., if no ballast adjustment is made, BD $= \Delta B$ and represents the change in net buoyancy resulting from the change in depth. If it is desired that $\Delta B = 0$ at the depth $Z_2$ then ballast must be added until $\Delta W =$ BD. BD obviously represents the number of isoballast-line intervals crossed by the temperature trace between the depths $Z_1$ and $Z_2$.

The chart may be used not only to estimate changes in buoyancy, or required changes in ballast, in moving between two stated depths as illustrated above but also to show what may be expected to happen in a variety of other circumstances.

For example, suppose a submarine in trim at point A in Figure 14 floods an amount of ballast $\Delta W$ while at the original depth $Z_1$. The state of the vessel will be represented by the point E and it will be heavy by the amount $\Delta W$, measured in isoballast-line intervals, which will cause it to sink. The question is at what depth, if any, it will come to trim with neutral buoyancy. The state of the vessel as it sinks is represented by the points along the isoballast line drawn through points E and B. At each depth this sloping line represents the temperature change required to compensate for the decreasing buoyancy due to compression in addition to the initial change in weight. If at some depth the temperature trace crosses this isoballast line, as at B, then at that depth the increase in buoyancy due to the temperature gradient will equal the decrease in buoyancy due to the added weight plus that due to compression and the submarine will again be in trim at that depth. If the submarine is caused to descend deeper, as to $B_1$, the loss in buoyancy represented by the continued course of the isoballast line drawn through B and E will be less than the gain in buoyancy represented by the temperature trace. The submarine will become light and must flood more ballast or decrease its depth if it is to come into trim.

### 6.1.3 Selection of Correct Bathythermograph Card

The isoballast lines each represent the locus of all points where the effect of temperature on buoyancy is equal and opposite to the effect of compression on buoyancy. The spacing of the lines with respect to temperature depends upon the displacement of the submarine; the spacing with respect to depth depends on the actual compression of the vessel and this varies, as shown in the preceding chapter, not only from one class of submarines to another, but also from one boat to another within a given class. It is consequently essential that BT cards be used with isoballast lines appropriate to the displacement and compression of the submarine.

Bathythermograph cards have been prepared for submarines of 2,400 tons submerged displacement having compressions of 1,400, 2,000, 3,000, 4,000, 6,000 pounds per 100 feet. By selecting a card for a compression nearest to that of the submarine, errors in ballast estimates larger than 500 pounds per 100 feet are avoided. The 1,400-pound card is recommended for the SS 285 and subsequent submarines, the 2,000-pound card for earlier fleet-type submarines, unless experience shows a different card is required. It is believed that compression estimates greater than 3,000 pounds per 100 feet are usually the result of entrapped air, and will not be encountered in properly conditioned submarines. The cards for 4,000- and 6,000-pound compressions are consequently being withdrawn from distribution.

## 6.2 PRECISION OF BATHYTHERMOGRAPH PREDICTIONS

The several factors which determine the precision of predictions of ballast change by the bathythermograph are enumerated below.

### 6.2.1 Buoyancy as a Function of Temperature

Temperature changes are recorded and may be read easily to about 0.5 C corresponding to buoyancy changes of about 150 to 450 pounds depending on the temperature. It is not easy to interpolate in reading isoballast-line intervals to less than 500 pounds. Frequently the zero setting of the temperature recording mechanism is wrong by several degrees. This does not introduce serious error since temperature differences only are involved.

The response of the thermal recording system is sufficiently quick, in relation to the speed of descent or ascent, that hysteresis is not present in the record provided the instrument is properly adjusted. Occasionally marked hysteresis is produced by excessive pen pressure, by bending of the copper tube which transmits the temperature effect, or by mechanical interference within the recorder.

The numerical relation of temperature to density used in constructing isoballast lines is known with great precision. The displacement of fleet-type submarines agrees with that assumed in the calculations to 4 per cent at least. Repeated experience of technicians, in observing the effect of shifting known quantities of ballast on the depth assumed by submarines balanced in strong temperature gradients, has confirmed the reliability of estimates of buoyancy change due to temperature.

Serious errors in estimating the proper compensation for temperature changes may arise, particularly if abrupt temperature gradients are encountered, because of the location of the blister housing the temperature sensitive element. The blister has usually been mounted on the conning tower fairwater, some 15 or 20 feet above the center of buoyancy. Consequently it does not record the temperature of the water which is displaced by the greater part of the hull, and which determines its buoyancy. This difficulty is being reduced in recent experimental installations by mounting the thermal element at the level of the bilge keel.

### 6.2.2 Buoyancy as a Function of Salinity

The BT does not take account of salinity gradients and may be significantly in error if they are present. This is the most serious source of error in the instrument. As discussed in Chapter 2 many parts of the ocean are free of substantial salinity gradients, and if they are present, some allowances for these effects may be made with the aid of the Submarine Supplements to the Sailing Directions described in Chapter 11.

### 6.2.3 Buoyancy as a Function of Depth

The BT reading of depth usually checks the depth gauge reading to within 5 feet. No serious error arises on this account except that occasioned by the location of the blister remote from the center of buoyancy. The determination of compression of individual vessels with precision is difficult. Experience indicates that individual submarines of a given class do not usually differ very much, and that better results are obtained by using an isoballast-line grid designed for the class, than using a special grid for each vessel.

Unfortunately several of the submarines first tested for compression gave abnormally high values, presumably because of entrapped air, and this led to the belief that submarines varied in compression more than they do in fact. Consequently, cards were issued covering a greater range of compressions than are necessary and this in turn led to many submarines receiving and using the wrong card. Standard practice now provides cards for compressions of 1,400, 2,000 and 3,000 pounds per 100 feet. With proper selection errors in estimates of changes in buoyancy with depth should not exceed 500 pounds per 100 feet.

### 6.2.4 Buoyancy as a Function of Weight

The predicted buoyancy change can only be checked, in practice, against the ballast change required in restoring trim after a change in depth. Errors in estimating the ballast change arise from the inaccuracies of the gauges with which ballast water is measured. As pointed out in Chapter 5 these may frequently amount to 500 pounds or more. Errors also arise from the difficulty in determining when net buoyancy is zero. These errors apply to both the initial trim and that finally achieved after a change in depth. Even with great care, departures from zero buoyancy of less than 500 pounds cannot be easily recognized. Unless the submarine is balanced or is moving very slowly, the planing forces discussed in Chapter 9 may conceal the presence of a net buoyancy of 1,000 pounds or more.

It is consequently believed that, unless substantial salinity gradients are present, the bathythermograph predictions are about as accurate as can be taken advantage of in view of the inaccuracy of the tank gauges and the trimming operations.

### 6.2.5 Adequacy of Predictions under Service Conditions

The patrol reports of submarines which have used the bathythermograph in service contain a number of testimonials to the adequacy of its predictions such as the following.

"There was a layer, invariably between 100 and 200 feet outside the 100-fathom curve. In each case the layer necessitated much flooding in to get down and pumping out to get back up. The bathythermograph predicted the necessary procedure nearly every time."

"It was found that in changing depth from periscope depth to 300 feet through a temperature gradient, the trim was never off more than 500 pounds whenever the card indications were followed."

"We checked the bathythermograph on each deep submergence for information of the Diving Officer which enabled him to adjust his trim so that during search following each attack while we were deep he never had to pump, blow or increase speed to maintain depth."

"Cards graduated to 2,000 pounds per 100 feet were used and ballast changes indicated agreed very nearly with those actually required. Most dives from periscope depth to 350 feet required flooding in about 5,000 pounds."

These reports represent selected testimony from submariners who have used the BT with understanding and perhaps under especially favorable circumstances. In some cases where difficulties have been experienced the result can be attributed to the presence of salinity gradients, in other cases to the use of the wrong isoballast-line grid. Thus one submarine reported:

"The bathythermograph was very helpful in indicating to the Diving Officer the presence of density gradients and whether they were positive or negative. However, it did not give a true indication of the amount necessary to pump or flood."

This submarine was found to be using cards designed for compressions of 4,000 to 6,000 pounds per 100 feet although it belonged to a class of 1,400 pounds compression. In a group of 49 submarines checked, it was found that 64 per cent were using the correct card, 20 per cent were using the wrong card, and 16 per cent were using cards without isoballast lines which had been issued before the introduction of this feature.

In order to obtain an overall impression of the precision of BT predictions under general service conditions, an examination has been made of BT records, returned by submarines to the Hydrographic Office, on which notations of the actual ballast change made in diving are entered. From the record itself the predicted ballast change has been estimated and compared with that actually made. All cases where there was evidence of unreliable trims due to high speed or other cause were eliminated and wherever the wrong isoballast-line grid was employed the record was transferred to the correct grid before the prediction was made. In some cases it is possible that the notation on the card was not properly interpreted.

In the case of 307 dives in which about 45 submarines participated the predicted ballast change agreed with that actually made within the following limits:

18 per cent shifted the predicted amount of ballast

49 per cent shifted within 1,000 pounds of the predicted amount

71 per cent shifted within 2,000 pounds of the predicted amount

81 per cent shifted within 3,000 pounds of the predicted amount

19 per cent shifted over 3,000 pounds more than the predicted amount

Thus it appears that the chances are about even that the prediction will fall within 1,000 pounds of the amount actually shifted. The predictions which err within this probable error are readily accounted for by the several sources of inaccuracy which have been discussed. It seems probable that the larger errors are in many cases due to poor trims either before or at the end of the dive or both. The records of 25 dives which were excluded from this study because they contained evidence that unsatisfactory trims had been achieved, chiefly because of high speed, show that in 18 cases (76 per cent) the ballast change differed from the prediction by more than 3,000 pounds. Undoubtedly in many of the dives included in the study, bad trims were obtained but were unrecorded.

A further breakdown of the data shows that of 253 dives in which the ballast change differed from the prediction, more ballast was shifted than the prediction called for in 130 cases (51.5 per cent) and less in 123 cases (48.5 per cent). This distribution suggests the absence of any preponderant systematic error in the predictions. A closer scrutiny shows, however, that this result is probably the consequence of two opposed tendencies.

When the observations made during descent are separated from those made during ascent it is found that in descent less ballast is shifted than called for by the prediction in 55 per cent, more in 45 per cent of the 157 cases. The tendency to shift less than predicted is particularly great in descents made under conditions of unstable buoyancy where pumping is called for. In 36 such descents less ballast was shifted in 61 per cent of the cases; more in only 39. There is thus evidence of a conservative tendency on the part of diving officers to shift as little ballast as need be, thus causing ballast changes to tend to be less than the predictions.

On the other hand, observations made during ascent reveal an opposite tendency. In 96 ascents it was found that more ballast was shifted than called for by the prediction in 63 per cent of the cases, less in 37 per cent of the cases. This disproportion was due to the dives made under stable buoyancy conditions when ballast was pumped out during ascent. In this group of 73 cases more ballast was pumped than predicted in two-thirds of the ascents. In 23 ascents in which ballast was flooded during ascent the amount flooded exceeded the prediction in 12 cases and was less in 11. The result may be explained by the fact, discussed in Chapter 7, that submarines tend to become heavy during deep submergence, from leakage and cooling of the ballast water. Consequently when they ascend, additional ballast water must be pumped to compensate for this gain in weight.

### 6.2.6 Errors Due to Salinity Gradients

It has been pointed out in Chapter 2 that within the depths accessible to submarines, large areas of the ocean are free of salinity gradients large enough to seriously affect diving operations. In many other regions, significant salinity gradients are known to occur. In order to see how greatly such gradients affect BT predictions, two groups of records were selected from those returned from submarines in service for further study. One group contained 98 cases in which the dive occurred in water believed to be free of significant salinity gradients; the second contained 106 cases in which the presence of salinity gradients could be predicted from information contained in the Submarine Supplements to the Sailing Directions. A comparison of these groups with the entire group is given in Table 2.

TABLE 2. Comparison of Ballast Changes with Bathythermograph Predictions.

| Difference between ballast change and prediction | Total group (307 cases) | Salinity gradients absent (98 cases) | Salinity gradients present (106 cases) |
|---|---|---|---|
| None | 18 | 18 | 19 |
| Less than 1,000 lb | 49 | 60 | 44 |
| Less than 2,000 lb | 71 | 85 | 64 |
| Less than 3,000 lb | 81 | 89 | 78 |
| More than 3,000 lb | 19 | 11 | 22 |
| Equal to prediction | 18 | 18 | 19 |
| More than prediction | 42 | 37 | 53 |
| Less than prediction | 40 | 45 | 28 |

Numbers indicate the percentage of cases in each category.

These statistics indicate that BT predictions are much more precise under conditions when salinity

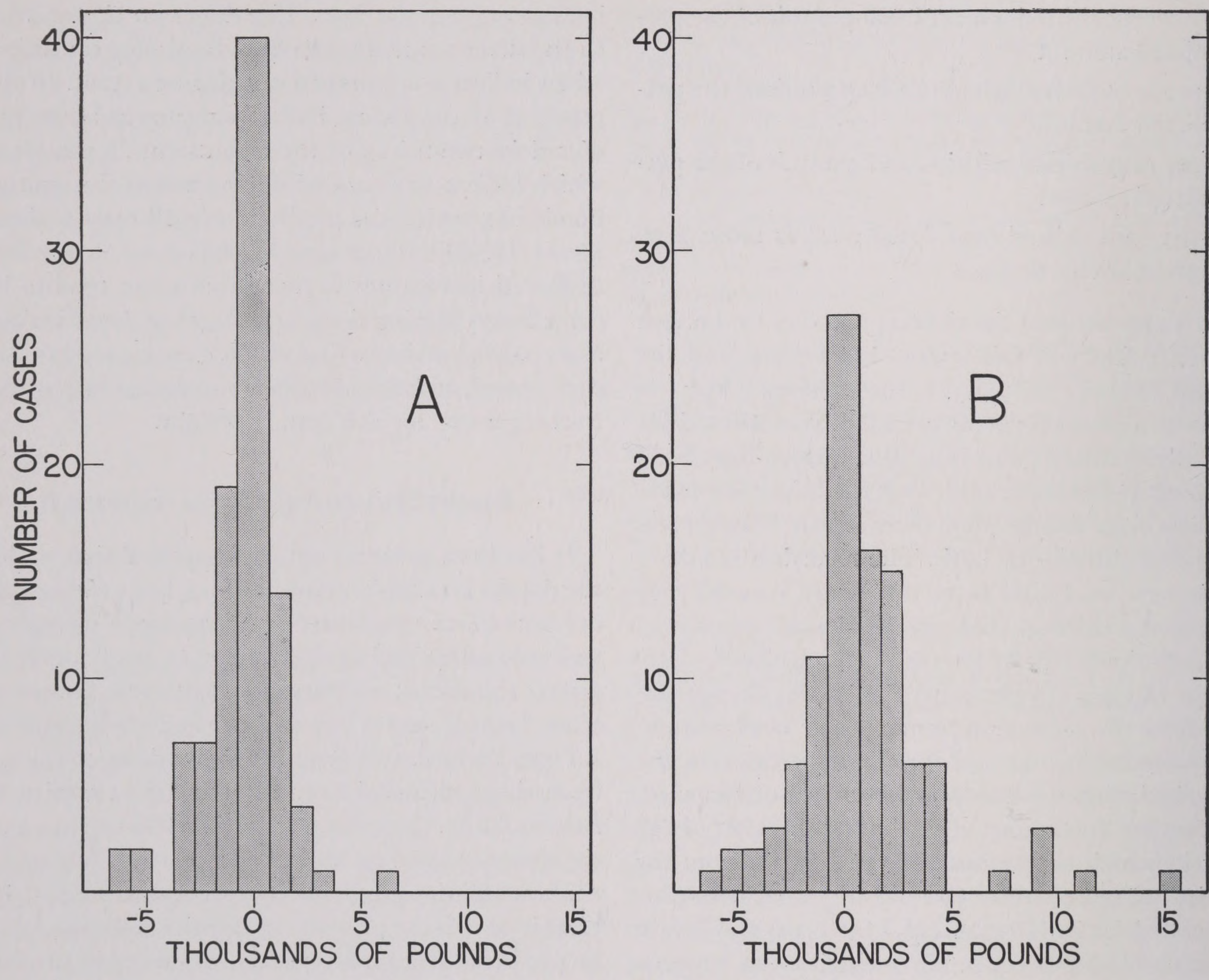


FIGURE 15. Frequency distribution of errors in bathythermograph predictions made by submarines in service.

A. Based on 98 cases in which errors due to salinity gradients were probably absent.

B. Based on 106 cases in which errors due to salinity gradients were probably present.

Ordinate—number of cases which fall in each class interval.

Abscissa—classes of error. Positive values indicate that ballast change exceeded prediction, negative that ballast change was less than prediction.

Class intervals are 1,000 lb except for the interval between +750 and −750 lb.

gradients are believed to be absent. Under such conditions there is a tendency to shift less ballast than is required by the prediction. The presence of salinity gradients very definitely decreases the proportion of errors which fall within any stated limit. These findings are brought out more clearly in Figure 15 which shows the frequency distribution of errors of different magnitude in the two series of data. Dives made in the presence of salinity gradients very definitely show an increase in the proportion of cases in which more ballast is shifted than called for by the prediction based on the BT tracing, and also indicate an increase in the magnitude of the errors in this direction.

Salinity errors in BT predictions are likely to arise in two sorts of situations. The first of these is in coastal waters where the effluence of rivers dilutes the surface waters and produces salinity gradients. These in turn accentuate the influence on density of the strong shallow temperature gradients which develop in summer (Figure 8, Chapter 2). The second is at the margins of the great currents such as the Gulf Stream or the Kuroshio where more dilute coastal water tends to overflow the saline oceanic water and produces a salinity gradient embedded in a positive temperature gradient (Figure 11, Chapter 2).

The following table illustrates the errors inherent in using the BT in the former situation. The data were obtained during tests with a United States sub-

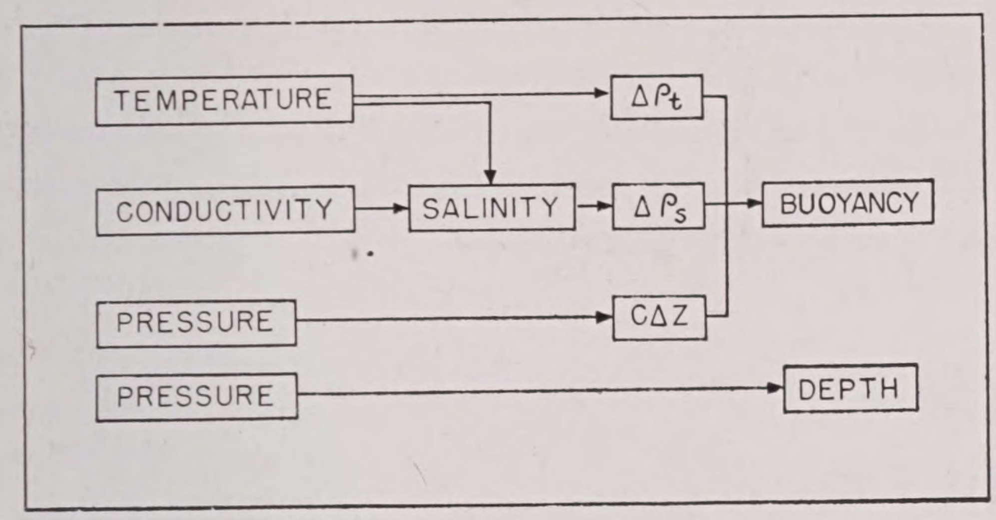


FIGURE 16. Arrangement of components of model CXJC buoyancy recorder.

marine in the Gulf of Maine off Portsmouth, New Hampshire, an area where strong shallow temperature gradients accompanied by salinity gradients occur in the late summer. The buoyancy changes due to salinity were estimated from chemical analyses of the water at the various depths.

TABLE 3. Comparison of Ballast Changes Required to Maintain Good Trim and Bathythermograph Predictions. Off Portsmouth, N. H., September 1943.

| Keel depth (feet) | Ballast change (pounds) | Bathythermograph prediction (pounds) | Error in prediction (pounds) | Buoyancy change due to salinity (pounds) |
|---|---|---|---|---|
| 64 | 0 | 0 | 0 | 0 |
| 77 | 7,100 | 5,000 | −2,100 | 2,600 |
| 100 | 8,100 | 5,500 | −2,600 | 3,070 |
| 200 | 8,100 | 6,000 | −2,100 | 4,100 |

Ballast changes in pounds are cumulative from 64 feet. Bathythermograph prediction assumes compression of 1,400 pounds per 100 feet.

It may be seen that the BT underestimated the ballast change by about 30 per cent. The error is rather more than accounted for by the measured salinity gradient.

To meet situations of this sort the following rule serves to warn the diving officer of the character of the errors produced by salinity gradients if present: When the temperature decreases with depth, the salinity gradient will occur at the same depth as the thermocline. In making ballast adjustments allow for greater increase in buoyancy than the BT record indicates.

Whenever cold coastal water overlies the warmer water of an ocean current it is certain that a salinity gradient is present, since otherwise the water column would be unstable and the stratified condition could not persist, as explained in Section 2.6. Under these circumstances, BT predictions based on the temperature gradient are quite misleading. This is illustrated by the following measurements made on a United States submarine during a dive off the southern coast of New England near the inner margin of the Gulf Stream. The hydrographic situation observed during this dive is illustrated in Figure 11, Chapter 2.

TABLE 4. Comparison of Ballast Changes Required to Maintain Good Trim and Bathythermograph Predictions Off Southern New England Coast April 1943.

| Keel depth (feet) | Temp. (F) | Salinity (‰) | Ballast change (pounds) | BT prediction (pounds) | Error in prediction (pounds) | Buoyancy due to salinity (pounds) |
|---|---|---|---|---|---|---|
| 90 | 41.1 | 32.99 | 0 | 0 | 0 | 0 |
| 150 | 41.1 | 32.94 | —2,000 | —1,200 | 800 | —210 |
| 200 | 43.7 | 33.40 | —2,000 | —2,200 | —200 | 1,720 |
| 250 | 49.4 | 34.54 | —1,000 | —6,800 | —5,800 | 6,510 |
| 275 | 51.3 | 34.88 | —1,000 | —8,100 | —7,100 | 7,940 |
| 312 | 52.8 | 34.90 | —3,000 | —9,700 | —6,700 | 8,020 |
| 90 | 42.6 | 33.06 | —1,500 | —600 | 900 | 290 |

Ballast changes in pounds are cumulative from 90 feet. Bathythermograph prediction assumes compression of 2,000 pounds per 100 feet.

It will be noted that although there is a very large error in the prediction, this error is rather closely accounted for by the measured salinity gradient. The salinity gradient coincides closely in depth with the temperature gradient, since both arise from the discontinuity of the layers of cold and warm water which occurs at the depth of about 200 feet. Actually very little ballast change was required, so closely did the

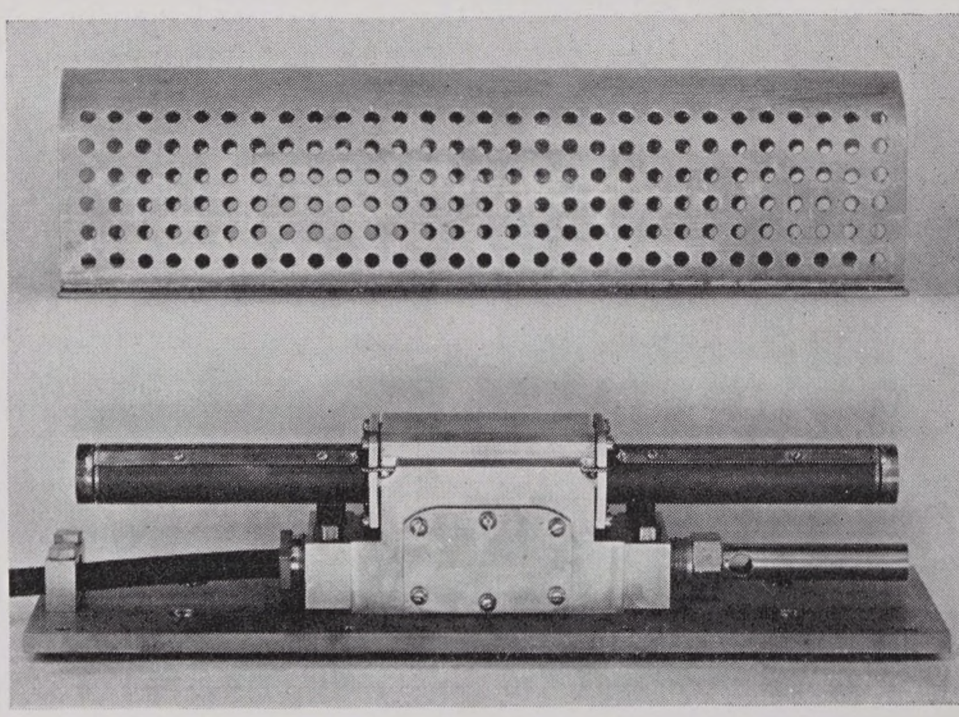

FIGURE 17. Measuring unit of model CXJC buoyancy recorder.

effects of temperature and salinity balance one another. At the depths where the gradients were strongest, however, the buoyancy actually increased, as shown by the fact that 1,000 pounds of ballast was pumped between 200 and 250 feet. The submarine was balanced at this depth in spite of the strong positive temperature gradient.

Observations of this sort have led to the following rule for ballast adjustments in the presence of positive temperature gradients:

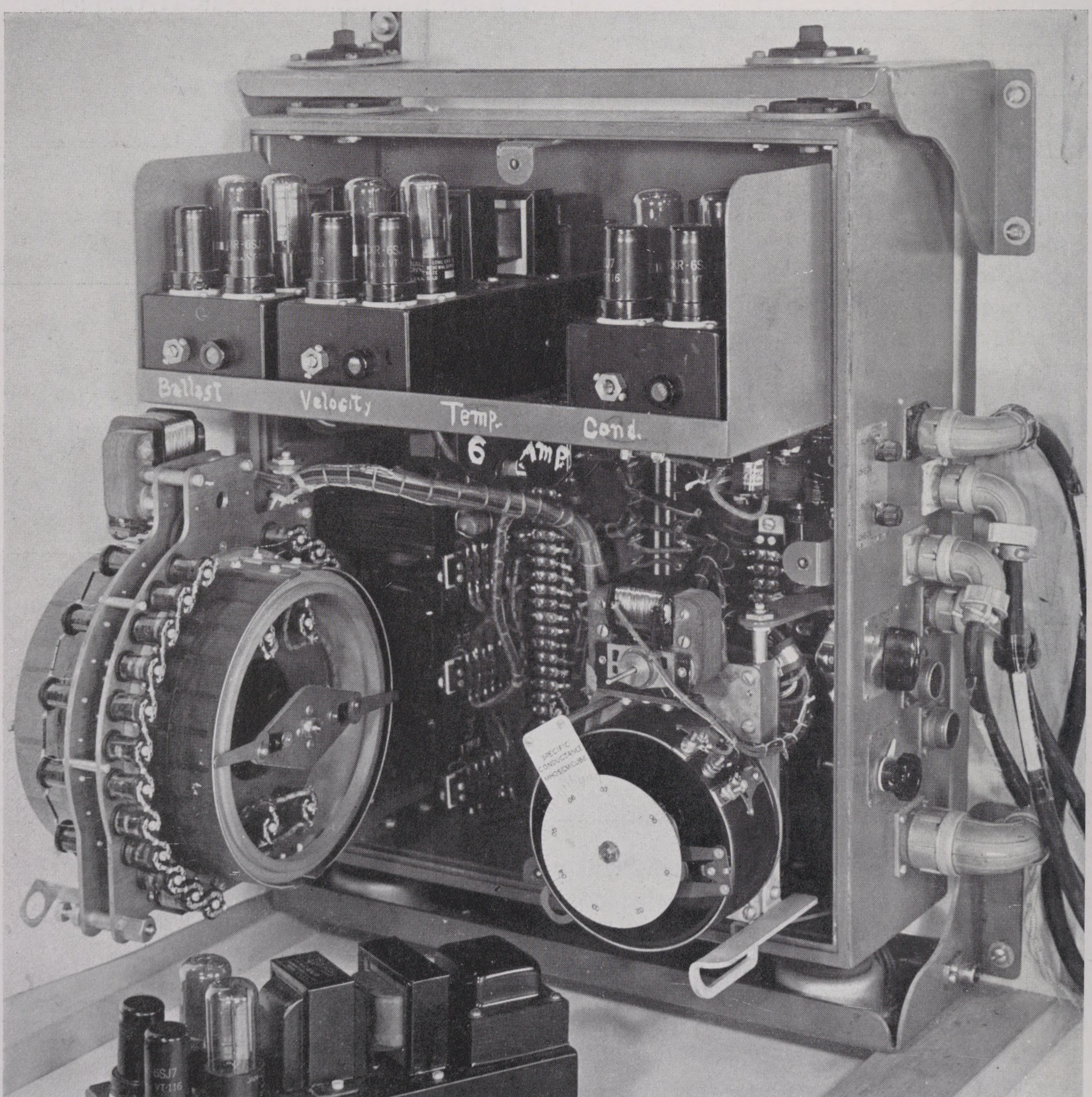


FIGURE 18. Model CXJC computing mechanism. The temperature bridge is swung out to give access to parts within. One amplifier has been removed.

When the temperature increases with depth, a salinity gradient is always present. It will at least counterbalance the influence of temperature on buoyancy. The isoballast lines cannot be used to predict ballast changes. Do not pump more ballast than when diving in isothermal water. The salinity gradient may be great enough to produce stable buoyancy; in this case ballast may need to be flooded on descent and balancing will be possible.

## 6.3 THE SALINITY CORRECTED BUOYANCY RECORDER

The model CXJC is an instrument which takes account of the salinity as well as the temperature of the water in which the submarine operates. In order to determine the ballast changes necessary to keep the vessel in good trim continuous measurements of temperature, salinity, and pressure are made.

The salinity of the water is determined by the simultaneous measurement of its temperature with the aid of a resistance thermometer and of its electric conductance using a conductivity cell. These two electrical measurements are combined by means of suitable computing mechanisms to yield a voltage proportional to the effect of salinity on the density of the water.

The temperature of the water is also converted by similar means to yield a voltage proportional to the effect of temperature on the density of the water.

The pressure of the water acting on a Bourdon spring controls an arrangement which yields a voltage proportional to the effect of compression with depth on the buoyancy of the submarine.

The three resulting voltages are combined to actuate a servo motor which moves the writing point of the buoyancy recorder horizontally in proportion to the change in buoyancy resulting from both the change in density of the water and the compression effect with change in depth.[b]

The system is shown schematically in Figure 16.

The CXJC is designed to include a second recording instrument which through similar mechanisms combines the temperature and conductivity measurements to write a graphic record of sound velocity as a function of depth. The details of the sonar recorder need not concern us, however.

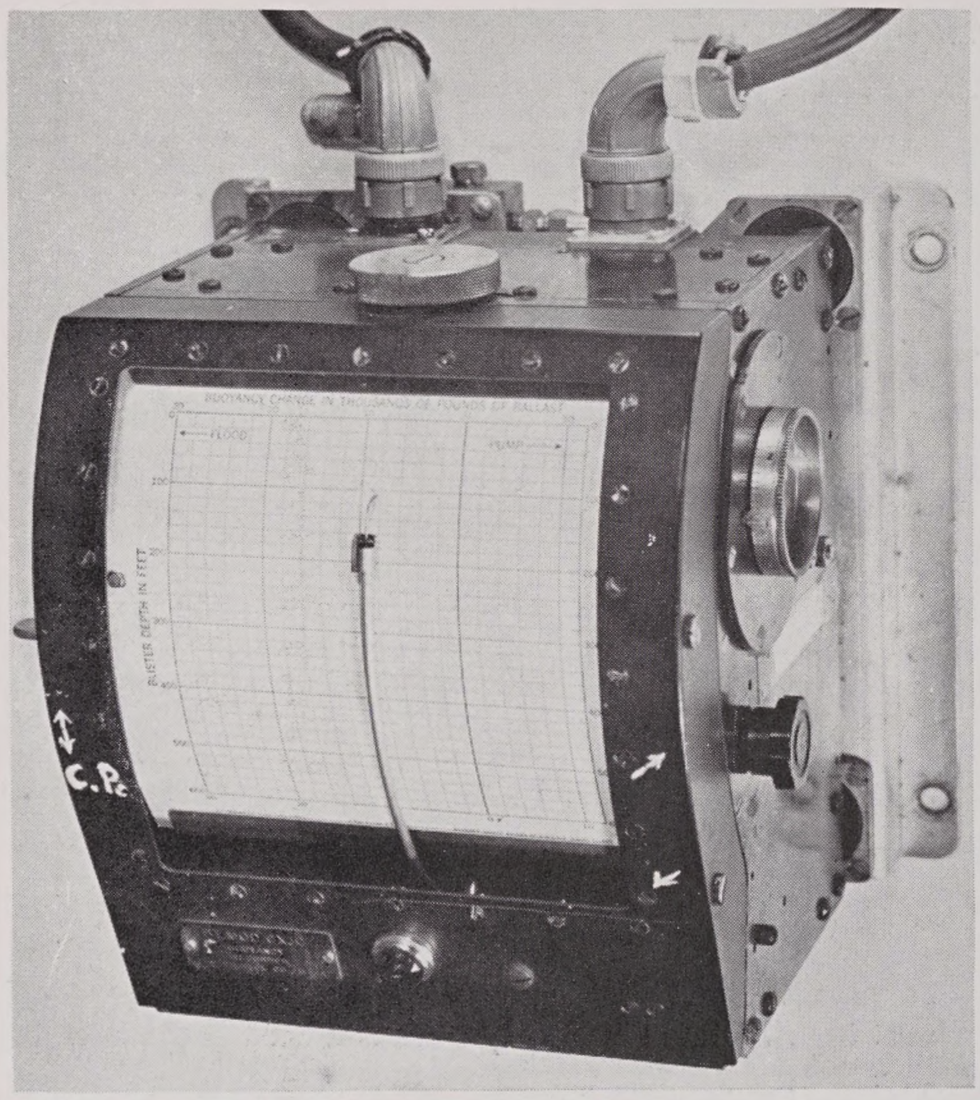


FIGURE 19. Model CXJC buoyancy recorder.

The measuring unit of the CXJC, which consists of a resistance thermometer bulb and a conductivity cell, can be mounted either in a line of circulating water within the vessel or external to the hull. (See Figure 17.) In the former position water is pumped through the cell and may be drawn from near the level of the center of buoyancy, which is the appropriate position in respect to buoyancy estimations. The internal position is advantageous since it permits ready cleaning to remove fouling growths. The external cell may be mounted high on the shears in a position favorable for securing information on sonar conditions close to the sea's surface and for obtaining advance information on buoyancy conditions during ascent. An external cell has also been designed which can be mounted at the lower end of a pipe passing downward through a main ballast tank so as to emerge at the level of the bilge keel. The pipe permits the measuring unit to be withdrawn for cleaning when the submarine is surfaced. The measuring units in the external positions depend on the motion of the vessel to force water through the conductivity cells.

The computing mechanisms are assembled for the

[b] The integration of the density function of temperature and the density function of salinity depends upon the approximation that the density function of temperature is the same at any salinity and that a given change in salinity has the same effect on density at any temperature. This assumption is not quite correct and leads to some error when measurements are made over very large ranges in temperature or salinity.

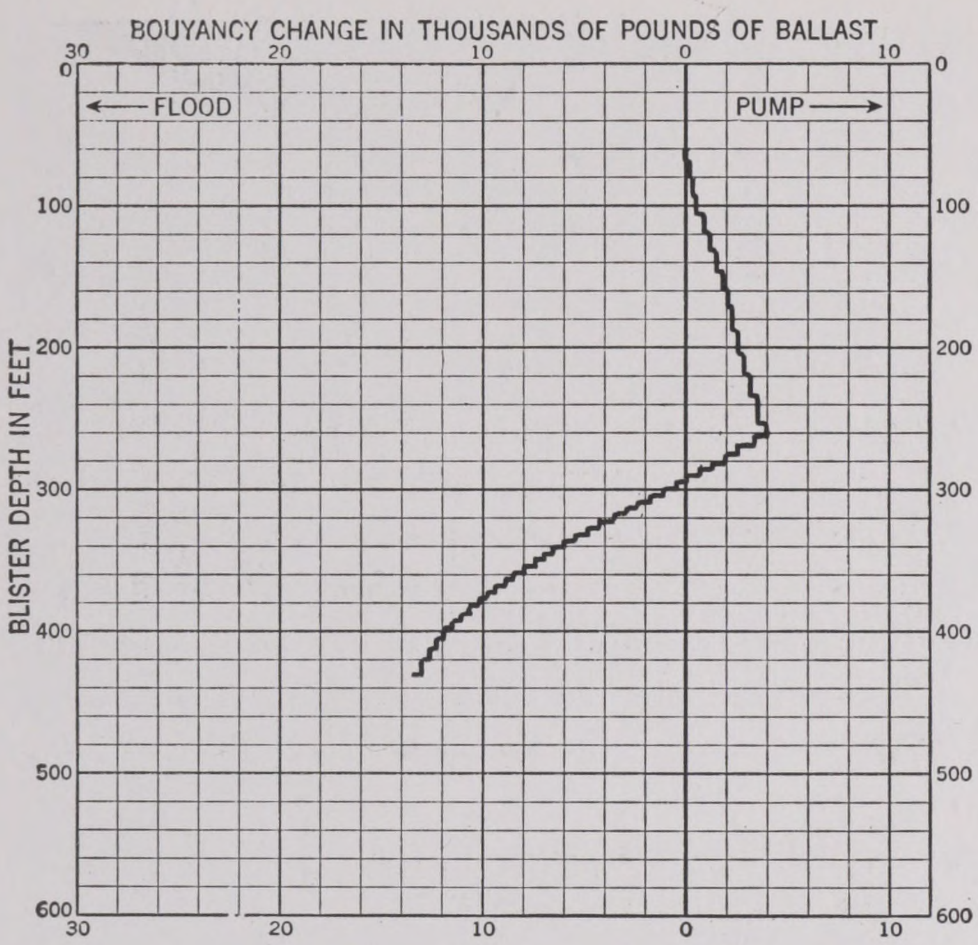


FIGURE 20. Chart used in model CXJC buoyancy recorder showing simulated buoyancy trace. Reduced to ½ natural size.

most part in a separate case which can be located wherever convenient. (See Figure 18.) The recorders are kept as compact as possible so as to be suitable for mounting on the diving-instrument panel.

The buoyancy recorder is pictured in Figure 19. It carries controls which permit recording to be switched from one of two alternate positions of the measuring units, i.e., from the shears to the center of buoyancy position. An automatic adjustment assures that the record will always show the condition of buoyancy at the depth where the measurement is made, irrespective of the position on the hull of the measuring unit.

An adjustment is provided so that the magnitude of the influence of compression with depth can be varied. The same instrument and card thus can be used with vessels of any compression.

The position of the pen which records the buoyancy is normally adjusted so that a zero setting may be made whenever a good trim is obtained. Subsequent buoyancy changes are thus indicated directly and can be used as a guide for ballast changes. This arrangement permits an expanded scale of good legibility to be used over the full range of density to be found in fresh or salt waters.

Figure 20 shows the card used in the buoyancy recorder of the CXJC. The record is drawn as it would appear for a boat of compression equal to 2,000 pounds per 100 feet, diving from periscope depth in water isothermal to 260 feet below which depth a strong density gradient is encountered. The part of the record sloping to the right from 50 to 260-foot depth indicates the result of compression, the sole influence on buoyancy while in water of uniform density. At 260 feet the submarine should pump 4,000 pounds to restore good trim. The record indicates that at 300 feet the buoyancy of the submarine would be the same as at periscope depth and no ballast adjustment would be required. To be in trim at 400 feet, the submarine should flood 12,000 pounds. This record is very much easier to interpret than that of the earlier types of bathythermograph. An experimental CXJC has been given preliminary tests. The results indicate that it will predict ballast changes as accurately as the submarine can be trimmed and its compression adjustment can be set. Table 5 shows the precision with which the buoyancy indications followed that of the sea water during a surface run through waters varying greatly in salinity.

TABLE 5. Comparison of Buoyancy Changes Recorded by CXJC and Those Calculated from Measurements of Temperature and Salinity.

| Temperature F | Salinity ‰ | Buoyancy change pounds Calculated | Buoyancy change pounds Recorded | Difference |
|---|---|---|---|---|
| 35.5 | 31.51 | 0 | 0 | 0 |
| 36.2 | 30.88 | 2,700 | 2,600 | +100 |
| 36.9 | 30.61 | 4,320 | 4,200 | +120 |
| 38.1 | 29.23 | 9,720 | 10,200 | −480 |
| 38.4 | 26.24 | 23,220 | 22,800 | +420 |
| 40.6 | 22.65 | 38,870 | 38,600 | +270 |

Table 6 shows a comparison of ballast changes and buoyancy predictions during several experimental test dives in water in which strong salinity gradients were present.

TABLE 6. Comparison of Ballast Changes with Predictions of CXJC.

| Depth—feet From | Depth—feet To | Ballast change—pounds CXJC prediction | Ballast change—pounds Actual change | Ballast change—pounds Difference |
|---|---|---|---|---|
| 60 | 400 | +6,000 | +5,000 | 1,000 |
| 400 | 200 | 0 | 0 | 0 |
| 200 | 100 | −2,000 | −2,000 | 0 |
| 60 | 400 | +2,000 | +2,500 | 500 |
| 400 | 100 | −1,000 | −1,300 | 300 |

## Chapter 7

# CHANGES IN BUOYANCY DURING PROLONGED SUBMERGENCE

SUBMARINES tend to become heavy during submergence. The effect is referred to as "soaking up" and is attributed to losses of air from the interstices of pervious structures such as woodwork and rope or cable and from the multiplicity of crevices in which it might be entrapped. How great the effect of such entrapped air may be is unknown. There are, however, at least three other sources of lost buoyancy during submergence: (1) the permanent set of the hull due to compression, (2) leakage, and (3) cooling of the hull, ballast water, and fuel oil.

The prevalence and magnitude of the soaking-up effect is indicated by records of ballast changes made by submarines in service. In a group of 68 dives made by 13 different vessels in which the ballast change on both descent and ascent was reported, more ballast was pumped than was flooded in 49 cases; in only 7 dives, more was flooded than was pumped. In 12 dives nearly the same amount was shifted in descent and ascent, but this included 8 cases in which no ballast was shifted. Figure 1 shows the frequency with which the ballast flooded differed from that pumped by various amounts. It shows that commonly the soaking-up effect amounts to about 2,000 pounds and that occasionally much larger effects are experienced.

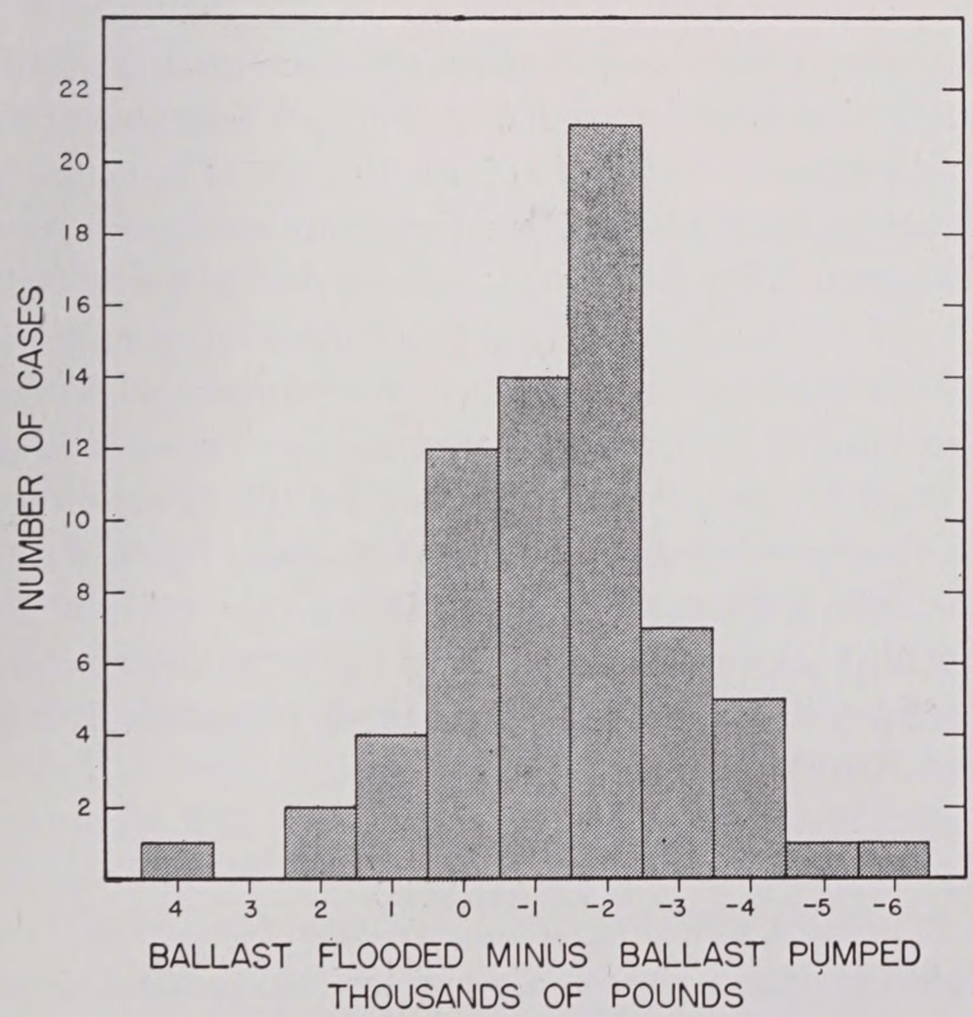


FIGURE 1. Frequency distribution of difference between ballast change on descent and on subsequent ascent by submarines in service. Ordinate—number of cases; abscissa—class intervals of 1,000 lb difference.

These reported dives were made for the most part in water in which considerable negative temperature gradients were encountered and the result may be due in part to a gain in weight resulting from the cooling of the ballast water. However, in the dives made in the absence of such gradients, the same discrepancy between the amount of ballast flooded and pumped existed which cannot be accounted for in that way.

Information on the prevalence of lost buoyancy during submergence is given also by the results of compression tests in which the apparent compression on descent is compared with the value obtained on ascent. If the submarine is becoming heavier from any cause during descent, more ballast will need to be pumped to obtain good trim at the greater depth than is required by the true compression and by the density gradients which may be present. Consequently, the compression estimate will be too high. On ascent, on the other hand, less ballast will be flooded and the compression estimate will be too low. The difference between the compression estimates on descent and ascent consequently gives a measure of the change in buoyancy during the dive.

Analysis has been made of 53 dives, made in the course of deep submergence tests on new construction submarines, in which compression was estimated both on descent and ascent. The difference between the estimates is presented as a histogram in Figure 2 which shows the number of dives in which the compression on descent exceeded that on ascent by various amounts. The mean difference is 1,200 pounds, the median difference 1,000 pounds, and the modal difference 600 pounds per 100 feet. When the data are separated into "good" and "poor" tests on the basis of the observers' judgment, it appears that the poor tests account for many of the large differences. This is explained by the fact that poor tests frequently arise from hasty trims on the return to periscope depth and that tests are judged poor if leakage is excessive. The good tests, however, show that the compression estimate is usually larger on descent than on ascent.

Further analysis of this data has failed to show any clear indication that the differences in compression estimates are related to the duration of submergence although this is to be expected. There is some slight suggestion that greater differences are obtained if dives are made into negative temperature gradients than in isothermal water or into positive gradients as is to be expected if cooling leads to a loss of buoyancy.

The results of this study are summarized in Table 1.

TABLE 1. Difference in Compression on Descent and Ascent. (pounds per 100 feet)

| | Number of tests | Mean | Median | Mode |
|---|---|---|---|---|
| All tests | 53 | 1,200 | 1,000 | 600 |
| All GOOD tests | 30 | 800 | 500 | 500 |
| All POOR tests | 13 | 1,900 | 1,700 | * |
| Duration of dive | | | | |
| All tests | | | | |
| Less than 2 hours | 20 | 1,000 | 1,000 | 1,000 |
| More than 2 hours | 24 | 1,300 | 1,000 | * |
| GOOD tests | | | | |
| Less than 2 hours | 11 | 700 | 500 | * |
| More than 2 hours | 14 | 800 | 500 | * |
| Temperature gradient | | | | |
| All tests | | | | |
| Negative | 23 | 1,400 | 1,200 | 700 |
| Isothermal or positive | 27 | 1,000 | 800 | 200 |
| GOOD tests | | | | |
| Negative | 11 | 1,000 | * | * |
| Isothermal or positive | 18 | 600 | 500 | * |

* Indeterminate.

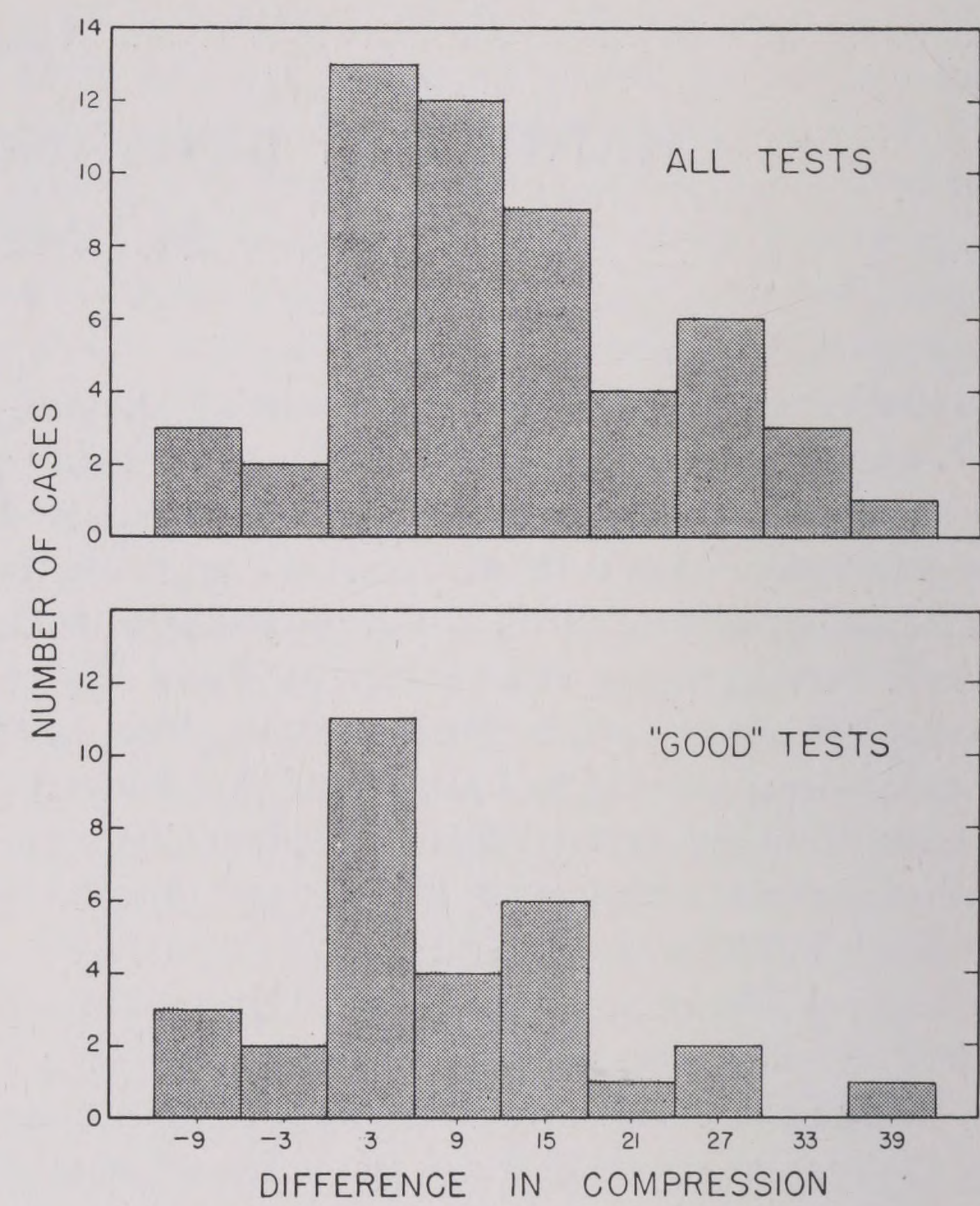


FIGURE 2. Frequency distribution of differences between compression estimates made on descent and ascent. The differences represent compression on descent minus compression on ascent. The difference in compression is shown in units of 100 lb; the class intervals corresponding to 600 lb.

## 7.1 PERMANENT SET OF HULL DUE TO COMPRESSION

Batten measurements have been made on submarines during the initial deep-submergence tests conducted in Lake Michigan off Manitowoc, Wisconsin. These measurements have shown that there is a permanent set of the pressure hull, when a submarine first submerges to the test depth, which decreases its diameter 0.01 inch on the average. This corresponds to a difference in buoyancy of approximately 200 pounds per 100 feet. The compression tests listed above were conducted on submarines during the initial deep submergence, although some boats had submerged previously to 200 or 300 feet and almost all had been to a depth of at least 100 feet. The range in depth during the compression tests averages about 300 feet. The permanent set of the pressure hull, therefore, can be expected to account for as much as 200 pounds of the difference in compression during the descent and ascent noted above. This effect accounts for only a small part of the difference noted in the "good tests" of new submarines being tested for compression. It seems unlikely that it is an important factor in the soaking up of submarines in service which previously have made repeated dives to considerable depths.

## 7.2 LEAKAGE

Submarines almost always leak somewhat. New vessels undergoing preliminary trials frequently leak severely as may those which have been damaged during service. The rate of leaking increases with depth and may be 10 or 12 times as great during deep submergence as at periscope depth. While it is impossible to make any quantitative generalizations in regard to rate of leakage, since this depends on the condition of the particular vessels, it is probable that leakage is often the principal factor causing submarines to become heavy during submergence.

## 7.3 COOLING OF HULL, BALLAST WATER, AND FUEL OIL

When a submarine descends into a temperature gradient, cooling of the hull, ballast water, and fuel oil may be expected to produce a loss in buoyancy. As a result, ballast may need to be pumped from time to time during a prolonged stay at deep submergence to retain good trim. If this compensation is not made, the ballast change required on returning to periscope depth will differ from that made in descent, and more ballast must be pumped out, or less flooded in, to regain good trim. After returning to the layers of warm water near the surface, a submarine which has cooled off during deep submergence will become lighter as it warms up and subsequent adjustments of trim may be required.

In order to estimate the magnitude of these effects, it is convenient to divide the displacement of the submarine into three parts, each displacing about 1.8 x $10^6$ pounds.

1. The displacement of the ends of the vessel which are exposed directly to the temperature of the sea water.

2. The displacement of the midpart of the pressure hull which is protected from the temperature of the sea by the main ballast and fuel tanks.

3. The displacement of the main ballast and fuel tanks.

The coefficient of linear thermal expansion of steel is 5.84 x $10^{-6}$ per degree F; consequently, the coefficient of cubic expansion of a steel structure will be 17.5 x $10^{-6}$ per degree F.

Consider first the immediate effect of entering water of *lower* temperature. It may be assumed that the exposed steel will at once acquire the temperature of the water but the temperature of the ballast water and fuel oil will remain unchanged. The contraction of the ends of the submarine will result in a decrease in buoyancy of 17.5 x $10^{-6}$ x 1.8 x $10^6$ or 31.5 pounds per degree F. The displacement of the pressure hull within the ballast tanks will remain unchanged. The contraction of the walls of the ballast tanks will cause some change in their displacement, but this will be almost exactly balanced by a loss in weight which results from the escape of an equal volume of water from the openings in the bottom of the tanks and the vents. Consequently, only the contraction of the ends of the submarine will contribute to the immediate loss in buoyancy and this will amount to only 31.5 pounds per degree F. This effect will not be detectable unless the temperature change exceeds 16 F and will never become important.

If the submarine remains in the water of lower temperature, the ballast water and fuel oil will become colder and more dense as the result of heat transfer through the walls of the tanks and because of an exchange of water between ballast tanks and sea by way of the available openings as the result of convection. When these processes have come to an end and the submarine is in *thermal equilibrium* with the sea water, the buoyancy will have decreased still further.

As the result of cooling the walls of the mid-section of the pressure hull within the ballast tanks, the dis-

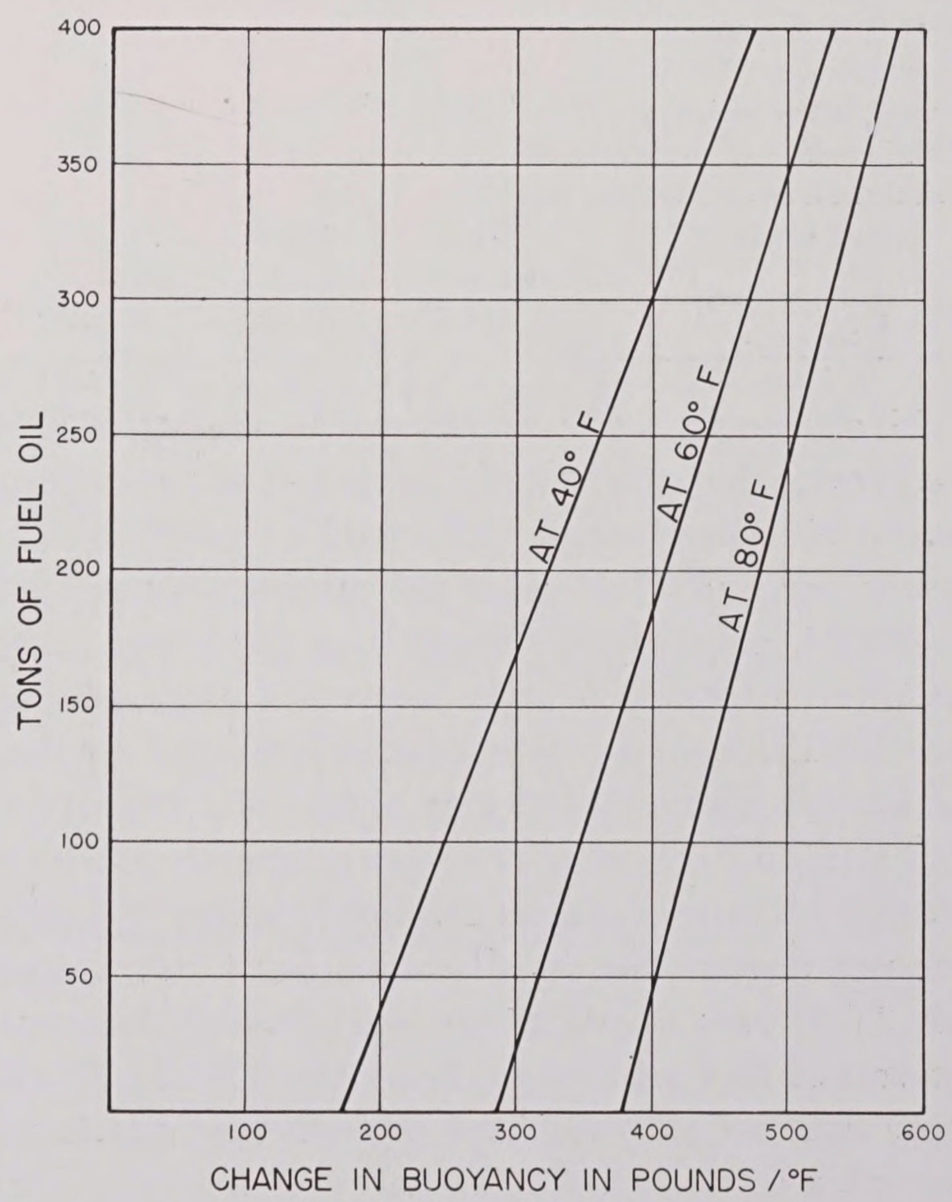


FIGURE 3. Relation between quantity of fuel oil carried and the change in buoyancy, as a result of cooling, of a submarine of 2,400 tons submerged displacement. Complete thermal equilibrium between the sea water and the contents of the ballast tanks is assumed.

placement will decrease 17.5 x $10^{-6}$ x 1.8 x $10^{6}$ or 31.5 pounds per degree F.

As a result of the cooling of the ballast water and fuel oil, the weight of the vessel will increase and the net buoyancy will be decreased accordingly. The change in density of the water per degree depends upon the temperature as indicated in Section 4.5. At 60 F it amounts to 0.000124 per degree F. Consequently, if the fuel oil tanks as well as the main ballast tanks were filled with sea water, the net buoyancy would decrease 0.000124 x 1.8 x $10^{6}$ or 223 pounds for each degree decrease in temperature.

The change in net buoyancy when a submarine attains thermal equilibrium at a temperature 1 F lower than that previously obtaining, assuming that all external tanks are filled with water, is summarized in Table 2.

TABLE 2. Change in Net Buoyancy of a Submarine of 2,400 Tons. Submerged Displacement Due to a Temperature Change of 1 F.

| Temperature F | 40 | 60 | 80 |
|---|---|---|---|
| $-\Delta\rho/F$ | 0.000060 | 0.000124 | 0.000175 |
| Decrease in Buoyancy (pounds per F) | | | |
| Immediate cooling of ends | 31.5 | 31.5 | 31.5 |
| Final cooling of mid-section | 31.5 | 31.5 | 31.5 |
| Final cooling of 800 tons of ballast water | 108.0 | 223.0 | 315.0 |
| Total | 171.0 | 286.0 | 377.0 |

The change in net buoyancy due to cooling of fuel oil is greater than that due to cooling of an equivalent amount of ballast water. The average change in density per degree for fuel oil of the specific gravity used is –0.0004, considerably more than for water. The maximum capacity of the Normal Compensating Fuel Oil Tanks of a representative fleet-type submarine is approximately 195 tons of fuel oil. The maximum total fuel oil capacity is approximately 350 tons of fuel oil. Figure 3 shows the total change in buoyancy per degree due to all causes for a submarine with 2,400 tons displacement and having different amounts of fuel oil aboard, from 0 to 400 tons. This graph assumes that thermal equilibrium has been attained, a condition which rarely exists.

It is evident from Figure 3 that substantial trim adjustments will be required to compensate for the effects of cooling if a submarine dives into water more than 4 or 5 degrees F colder than that from which it is in equilibrium at the start. The more fuel oil aboard, the more pronounced will be the loss of buoyancy due to cooling. The effects will be particularly pronounced if the water and fuel oil in the tanks is warm, i.e., when operating in the tropics or in late summer.

The influence of the various effects of cooling on the buoyancy of a submerged submarine is illustrated in Figure 4. Curve A illustrates the way in which buoyancy changes as the result of the effect of temperature on the density of the displaced water, assuming no change in the displacement of the submarine. Curve B is corrected to include the immediate change in buoyancy due to the contraction of the ends of the hull which are not protected by the ballast tanks.[a] Curve C shows the relative buoyancy of the submarine with all main ballast and fuel oil tanks filled with water and assuming this ballast water to be in thermal equilibrium with the sea at each temperature. Curves D, E, F, and G show relative buoyancy in thermal equilibrium with various amounts of fuel oil aboard.

The change in buoyancy arising from the cooling of the contents of the ballast tanks is related to the change in buoyancy which the vessel experiences when it first changes depth, since both depend on the change in temperature encountered. Roughly speaking, since the ballast tanks account for one-third the total displacement, one-third of the increase in buoyancy encountered on diving into colder water will be lost as the contents of the tanks cool. Consequently, about one-third of the ballast flooded in during a descent may need to be pumped out again as the cooling takes place.

While this may serve as a useful working rule in anticipating the effects of cooling during prolonged submergence, it is not very precise. More exactly, the quantity of fuel oil present in the ballast tanks and the effect of compression on buoyancy must also be taken into account. The fundamental relations are as follows:

Let: $\Delta W_t$ = change in weight due to cooling of ballast tank contents.

$R$ = fraction of displacement, $V$, occupied by ballast tanks.

[a] Since this effect is small, it has not been taken into account in buoyancy calculations or in the design of bathythermographs. With improvements in the art of trimming submarines, it may become desirable to do so.

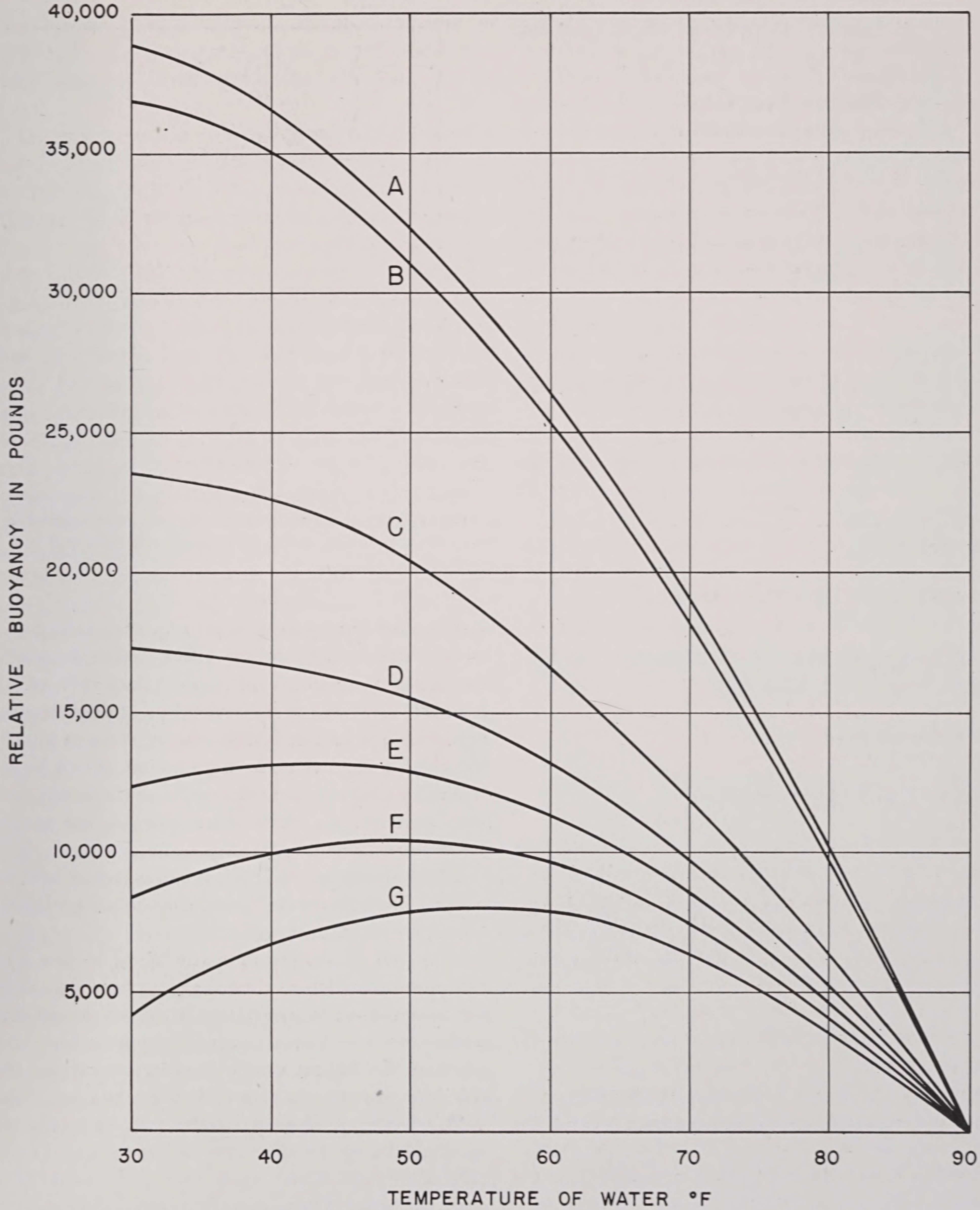


FIGURE 4. Effect of temperature on the buoyancy of a submarine of 2,400 tons submerged displacement:

A. Assuming no change in displacement of hull due to cooling.

B. Allowing for immediate cooling of steel of ends of hull.

C. Allowing for thermal equilibrium between sea water and content of ballast tanks and assuming 800 tons displaced by ballast tanks to be occupied by sea water.

D. Same but assuming 100 tons of fuel oil to be present in ballast tanks.

E. Same but assuming presence of 200 tons of fuel oil.

F. Same but assuming presence of 300 tons of fuel oil.

G. Same but assuming presence of 400 tons of fuel oil.

$r =$ fraction of displacement, $V$, occupied by fuel oil ballast.

$R - r =$ fraction of displacement, $V$, occupied by sea water ballast.

$\Delta\rho_t =$ change in density of sea water due to cooling.

$\Delta\rho'_t =$ change in density of fuel oil due to cooling.

Then:

$(R\text{-}r)V\Delta\rho_t =$ change in weight due to cooling of sea water ballast.

$rV\Delta\rho'_t =$ change in weight due to cooling of fuel oil ballast.

Therefore:

$$\Delta W_t = (R - r)\, V\Delta\rho_t + rV\Delta\rho'_t. \tag{1}$$

If $K$ equals average ratio of $\Delta\rho'_t$ to $\Delta\rho_t$ over the temperature range in question then:

$$\Delta\rho'_t = K\Delta\rho_t.$$

Equation (1) may then be written:

$$\Delta W_t = [R + (K-1)r]\, V\Delta\rho_t. \tag{2}$$

In order to compare the change in weight due to cooling with the change in ballast, $\Delta W$, required to adjust buoyancy at the time of the dive, we may write equation (5), Section 3.3 as:

$$\Delta W = V\Delta\rho_t + C\Delta Z, \tag{3}$$

substituting $\Delta\rho_t$ for $\Delta\rho_{ts}$ since salinity effects must be left out of account. Combining equations (2) and (3):

$$\Delta W_t = [R + (K-1)r]\,(\Delta W - C\Delta Z). \tag{4}$$

In order to see the numerical meaning of equation (4) we may take $R = 1/3$. Depending on the amount of fuel oil carried, $r = 0$ to $1/6$. $K =$ about 4 at a temperature of 60 F. Consequently, if the ballast tanks are completely filled with sea water the increase in weight due to cooling will equal one-third the ballast flooded during descent plus one-third the gain in weight due to compression. If the fuel tanks contain the maximum amount of fuel oil then $R + (K-1)r$ equals 5/6. The increase in weight due to cooling will equal 5/6 the ballast flooded during descent plus 5/6 the gain in weight due to compression. It may be seen from this that without taking the quantity of fuel oil into account, an exact allowance for the gain in weight due to cooling cannot be made.

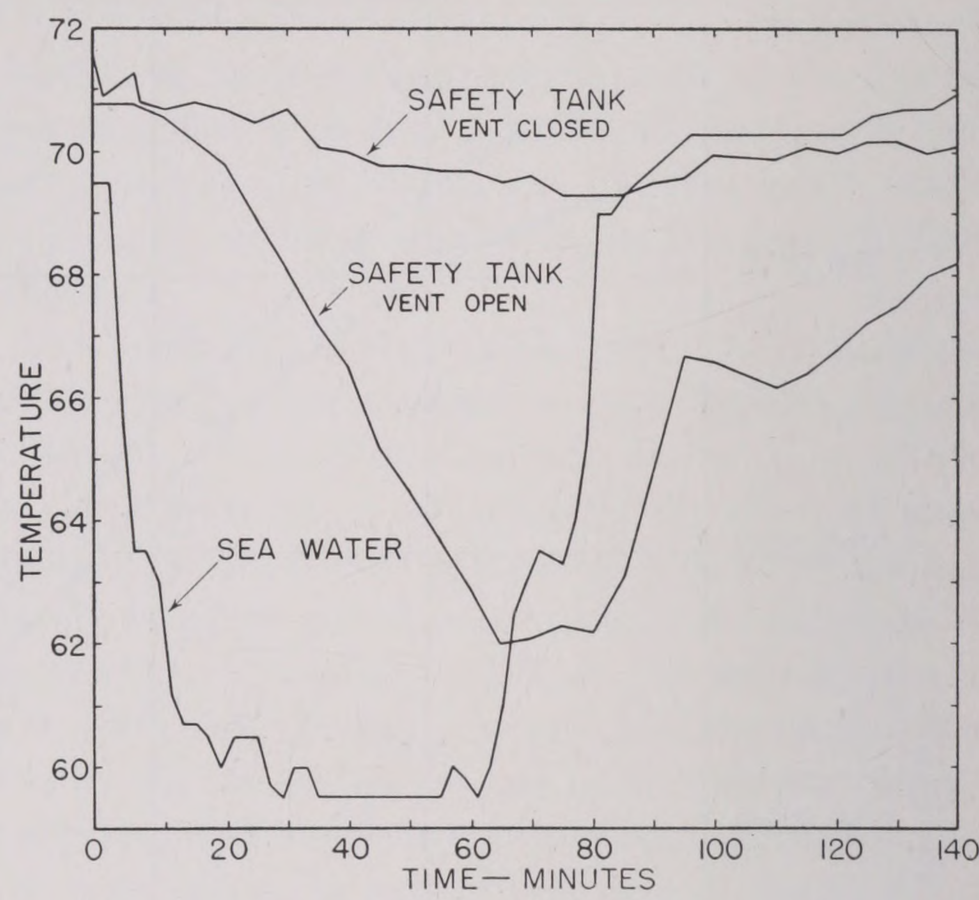


FIGURE 5. Temperature of ballast water in safety tanks, with vents open and closed, during deep submergence in a negative temperature gradient and after return to periscope depth.

The importance of cooling ballast water and fuel oil will be discussed further in connection with stable buoyancy in the following chapter.

The rate of cooling or warming of ballast water which occurs when a submarine is exposed to a different temperature depends on whether the vents of the ballast tanks are closed or open, and probably also on whether the ballast water is colder or warmer than the surrounding sea water. If the vents are closed, heat transfer is limited by the rate of conduction through the steel wall of the ballast tank and by the rate of mixing of the water within the tank. If the vents are open during descent, convection causes the ballast water to escape from the tanks through the vents to be replaced by sea water at the temperature of that surrounding the hull. On ascending into warmer water, colder ballast water can escape through the larger openings in the bottom of the tanks as the result of convection even though the vents are closed.[b] The rate of cooling of the fuel oil is limited by conduction through the wall of the tank and by the rate of mixing of the fuel oil within the tank.

The results of an experiment to test the rate of change of the temperature of the ballast water are illustrated in Figure 5. The tests were conducted with a United States submarine in the Gulf of Panama in March 1943 when a temperature gradient of about 12 F was present. On submerging, the submarine filled the ballast tanks with water of 72.5 F and after coming to trim briefly at 53 and 120 feet finally leveled off at 220 feet depth where she remained for 1 hour. During this dive the temperature of water drawn from the inboard vents of the safety tanks was measured, as well as that of the surrounding sea water, drawn from a pressure line in the forward torpedo room. The outboard vent of the starboard safety tank was kept shut during the test, that of the port tank was left open.

The results show that in the tank with the outboard vent closed the temperature of the water changed very slowly. The rate is only 1.5 F per hour during the period when the temperature difference is 10 F. In the tank with the outboard vent open the temperature change is very much more rapid. The temperature difference has been reduced by 80 per cent after 55 minutes in the colder water at 220 feet keel depth. On returning to the warmer water near the surface the tank with open vent warmed much more rapidly than it cooled during descent.

The difference in the rate of temperature change in the tank with open vent on descent and ascent is explained by the position from which the samples of water were drawn. The inboard vents are located at the top of the ballast tanks. On descent the warmer water of the tank escapes from the outboard vent and it is not until the colder water, entering at the bottom reaches the top, that its effects are felt. On ascent, on the other hand, warm water flows into the tank through the outboard vent under convective forces and at once reaches the point at which the samples are drawn.

This consideration indicates that the method employed is not very satisfactory. More useful results could be obtained by holding the submarine at constant depth below a thermal gradient and carefully determining the ballast adjustments required to maintain stop trim at that depth from time to time, or by observing the rate at which a submarine sinks while balanced in a thermocline, under conditions such that the buoyancy of the surrounding water can be adequately measured.

These experiments show quite satisfactorily, however, that the rate of cooling of the ballast water is very slow if the vents are kept closed and that a submarine may become markedly heavy within less than an hour if the vents are open. Consequently, whenever it is necessary to remain at depth for some time without operating the trim ballast pump, the vents should be closed unless other considerations require that they be left open.

Four observations on the loss of buoyancy due to cooling have been made on fleet-type submarines operating in the Key West area and are recorded in Table 3. The submarines remained submerged at some depth for several hours during which the ballast change required to main trim was recorded. If these results are compared with the values in Figure 3, it will be seen that the change in buoyancy per degree is greater than that predicted from Figure 3. The difference is probably due to leakage. There is no information on the amount of fuel oil aboard during any of these tests.

TABLE 3. Loss of Buoyancy Due to Cooling During Deep Submergence.

| Duration of submergence | Surface temp. | Temperature decrease at depth of submergence | Ballast change (pounds) | Decrease in buoyancy (lb per F) |
|---|---|---|---|---|
| 5 hrs. 30 min. | 71° | 4° | −4,100 | 1,033 |
| 3 hrs. 30 min. | 68° | 8° | −3,400 | 425 |
| 5 hrs. 10 min. | 64° | 7° | −5,800 | 830 |
| No record | 74° | 6° | −4,500 | 750 |

[b] It must be assumed that if a submarine descended into a density gradient due to salinity, convective forces would produce changes in the weight of the ballast water if the vents are open, but no information is available on this situation.

## Chapter 8

# STABLE BUOYANCY

If the density of the sea water is very nearly uniform a submarine will become heavier as it descends or lighter as it ascends because of the effect of compression. Any small deviation from the depth at which net buoyancy is zero will produce changes in buoyancy which cause the vessel to move in a direction which leads to still greater changes in buoyancy. Consequently, no matter how carefully trim is adjusted to secure neutral buoyancy, constant attention is required to hold the submarine at the desired depth with the use of the diving planes. Under these conditions buoyancy is *unstable*.

In contrast, if the density of the sea water increases with depth sufficiently, the influence of compression on buoyancy is outweighed by the density gradient and the submarine becomes lighter as it descends and heavier as it ascends. Any small deviation from the depth at which net buoyancy is zero will produce changes in buoyancy which cause the vessel to return to its original depth. Consequently, the submarine will hold automatically the depth for which it is trimmed. If the vessel is not exactly in trim, it will tend to seek the level at which net buoyancy is zero. Under these conditions buoyancy is *stable*.

It is a great advantage to be able to recognize the depths at which buoyancy is stable, since by seeking these depths the submarine can be controlled with greater ease. The submarine may be actually brought to a stop and allowed to float in the density layer without use of the planes to control its depth; this operation is known as *balancing*.

Two conditions of stable buoyancy may be distinguished. The first we may call *immediate stability*. It refers to a submarine which has been brought to its depth from a region of different temperature and as a result is not in thermal equilibrium with the surrounding water. Such a vessel will tend to hold its level for a time, but as the ballast water changes its temperature, its weight changes and the submarine will tend to sink or rise slowly depending on whether the ballast water is cooling or becoming warmer. The condition is not strictly a stable one and might better be described as pseudo-stability.

The second condition of stable buoyancy obtains after the submarine has come into complete thermal equilibrium with the surrounding water. We will call this *permanent stability,* since the vessel will now hold its position in a sufficient density layer indefinitely.

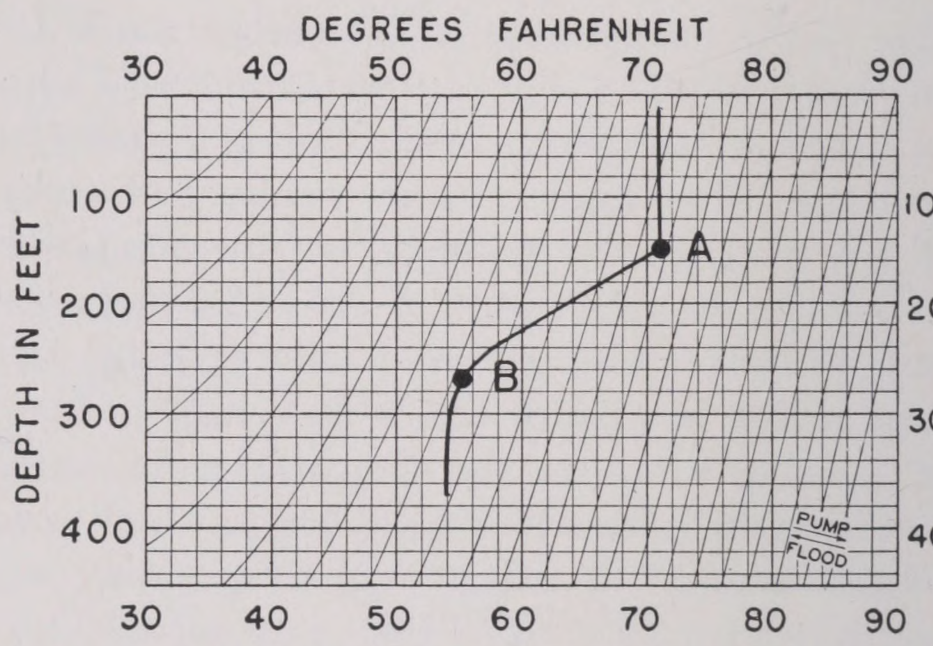


Figure 1. Temperature trace illustrating condition when immediate stability exists between depths $A$ and $B$.

## 8.1 IMMEDIATE STABILITY

The conditions for stability are fulfilled whenever $\triangle B/\triangle Z$ has a positive value. If a submarine is in good trim at some depth, $Z$, and no change in ballast is made and time is not permitted for the ballast water change temperature, it follows from equation (4), Section 3.2 that the change in buoyancy on changing depth is given by:

$$\triangle B/\triangle Z = V\triangle\rho_t/\triangle Z + C\,.$$

Remembering that $C$ is a negative number, it is evident that the conditions for immediate stability are fulfilled when:

$$V\triangle\rho_t/\triangle Z > -C\,.$$

Since $V\triangle\rho_t/Z$ is represented by the slope of the temperature trace on the bathythermograph card and $-C$ is represented by the slope of the isoballast lines, it follows that at any point where the temperature trace is inclined from the vertical more than the isoballast lines passing through the tracing at that point, immediate stability exists. (See Figure 1.)

By reference to Section 3.3, it may be seen that the

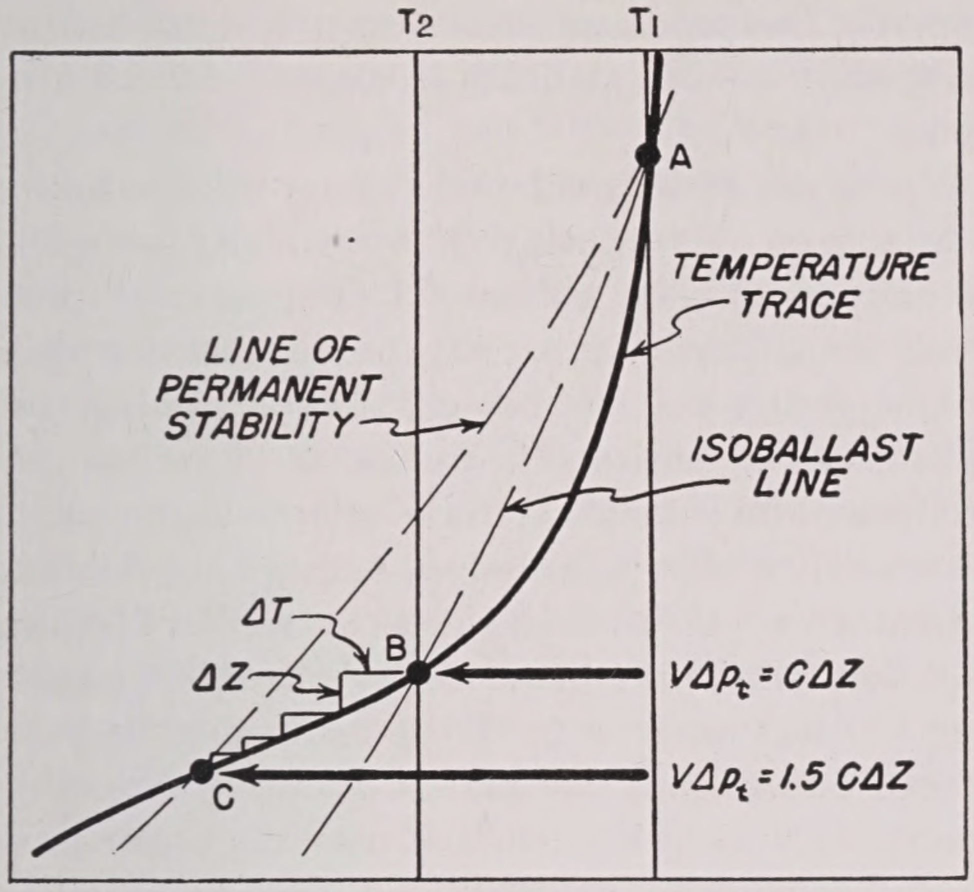


FIGURE 2. Diagram illustrating the change in depth of a submarine which when in trim at $A$ descends and balances at $B$ and subsequently becomes heavier as the result of cooling.

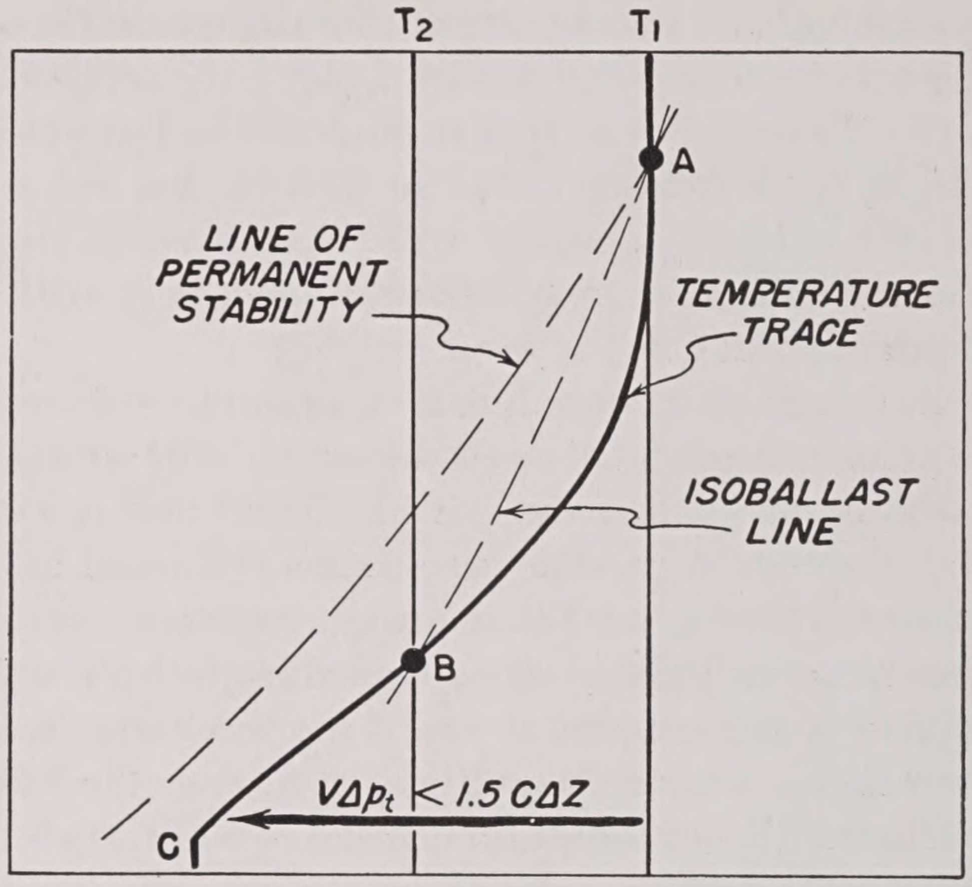


FIGURE 3. Diagram illustrating condition when permanent stability does not exist.

condition for immediate stability corresponds to that in which ballast must be flooded as the submarine descends. Consequently, wherever a submarine finds that ballast must be flooded in order to descend in trim it is passing through a region of stable buoyancy.

## 8.2 PERMANENT STABILITY

In order to define the conditions for permanent stability, consider a submarine changing depth so slowly that the ballast water is at all times in thermal equilibrium with the surrounding water. If the fuel oil ballast tanks were filled with sea water, the buoyant force due to the displacement would be due solely to the displacement of the pressure hull, since the weight of the ballast water is at all times equal to the weight of the water displaced by the main ballast tanks. The small changes in buoyancy resulting from the thermal contraction of the steel hull may be disregarded.

If $R$ equals the fraction of the submerged displacement, $V$, occupied by the ballast water, then the change in buoyancy resulting from any change in depth, $\Delta Z$, is given by $(1-R)V\Delta\rho_t/\Delta Z$ and $\Delta B/\Delta Z = (1-R)V\Delta\rho_t/\Delta Z + C$. Conditions of stable buoyancy are now fulfilled wherever:

$$V\Delta\rho_t/\Delta Z > -C/(1-R).$$

Since $R$ equals about 1/3, stability obtains when $V\rho_t\Delta Z$ is greater than $-1.5\ C$. This means that wherever the temperature trace is inclined to the vertical more than 1.5 times the inclination of the isoballast lines, buoyancy is permanently stable.

It is possible to draw lines on the bathythermograph chart which define by their slope the conditions of permanent stability in the same way that the ordinary isoballast lines define the conditions of immediate stability. They may be called *lines of permanent stability*. They represent conditions of equilibrium in respect to both temperature and buoyancy. Their inclination is 1.5 that of the isoballast lines. Such lines have found no use in practice as yet but they are helpful in considering buoyancy problems.

Example: In Figure 2, suppose a submarine in trim at point A where its ballast water is at the temperature $T_1$ descends without changing ballast. On reaching the depth of point B it will again be in trim, since at that depth the loss in buoyancy due to compression $C\Delta Z$ equals the gain in buoyancy $V\Delta\rho_t$ resulting from the thermal gradient. Since the temperature trace is inclined to the vertical more than the isoballast line, immediate stability exists and the submarine may balance at B. In this position, however, the submarine is surrounded by water of temperature $T_2$ which is colder than the ballast water. The cooling of the latter will cause a small increase in weight $\Delta W$ and the submarine will sink through the depth $\Delta Z$ until it is again in balance. This process will be repeated and the point representing the condition of the vessel will move downward along the temperature trace until C is arrived at; there the ballast water will be in thermal equilibrium with the sea and no further changes in weight will result from cooling and the submarine may balance indefinitely at the depth of point C.

By this graphic procedure an idea can be obtained as to how deeply a balanced submarine will settle as it cools and whether there is likelihood that it will "fall through" a given density gradient. Thus, it may be seen from Figure 3 that if the temperature trace does not cross the line of permanent stability which originates at the point at which the submarine was originally in thermal equilibrium, A, then the submarine will never come into thermal equilibrium but will settle until it reaches the point C below which even temporary stability does not obtain.

From consideration of these examples it is evident that the following rough rule indicates when a balanced submarine is in danger of ultimately sinking through a density layer as the result of cooling.

If at the depth of a balanced submarine, or at some greater depth, the temperature trace is not inclined to the vertical $1\frac{1}{2}$ times more than the isoballast lines which cross it, then permanent stability will never be reached and the submarine will ultimately sink below the density gradient.

Unfortunately, the high coefficient of thermal expansion of fuel oil, and the variable quantity of oil which is carried from time to time limits very greatly the utility of this rule. Fuel oil will increase in density on cooling much more than the sea water which it displaces, particularly at low temperatures at which the thermal expansion of sea water is relatively small. Consequently if much fuel oil is present and if the temperature of the sea water is low, much stronger temperature gradients must be present to ensure permanent stability than are indicated by the foregoing discussion. Indeed permanent stable buoyancy may be an impossibility. Reference to Figure 4, Chapter 7, shows that at low temperatures, submarines carrying 200 tons of fuel oil or more actually lose buoyancy as the temperature of the water with which they are in equilibrium decreases. Under such conditions $\triangle B/\triangle Z$ would have negative value in a negative temperature gradient and buoyancy would be unstable. However, since the rate of cooling of the fuel oil must be very slow, as judged by the rate of cooling of ballast water when the vents are closed, these effects of fuel oil on stable buoyancy will not become important unless balancing is continued for a long time.

Up to the present time no precise information is available on the rate and degree to which submarines actually sink when balanced in temperature gradients, though the fact that they become heavier while submerged is well established. The foregoing considerations are entirely theoretical and have been introduced into submarine doctrine only to the extent of a warning that balanced submarines are liable to settle through the thermocline as the result of cooling and that density gradients of less than 3,000 pounds per 100 feet are unreliable for balancing. It is, of course, pointed out that danger of falling through is least if balancing is attempted near the upper limit of the temperature gradient, and if the main ballast tank vents are kept closed during the operation.

## 8.3 BALANCING

In the past the operation of balancing has been regarded as a stunt, so unreliable that the practice has been officially discouraged. This prejudice arose from the fact that no means were available to indicate whether the submarine could expect to balance or not, and submarines were balanced only accidentally when their movements were checked by encountering heavy density layers or when they happened to come to trim in a region of stable buoyancy. It also happened sometimes that submarines attempting to balance without adequate knowledge of the density conditions would unexpectedly begin to sink, and as a result fear was always present that the vessel would fall through the density layer and get out of control.

The bathythermograph has provided a reliable means of predicting whether balancing is possible, at what depths it is feasible, and what margins of safety exist when balanced at any depth. Since its introduction, scores of submarines have recorded the operation in their patrol reports, occasionally under conditions in which it was of great value. In one case a submarine reports balancing for as long as 17 hours. The uses of the maneuver will be discussed in Chapter 10. Here it is sufficient to report that conditions where balancing is possible are much more frequent than was formerly realized and that the strength of the requisite gradients appears to be smaller than was anticipated.

While the possibility of balancing depends upon the rate at which the density of the water increases with depth, $V\Delta\rho_{ts}/\Delta Z$, and the security depends on the extent of the gradient below the vessel, as discussed above, the ease of bringing the submarine into balance at any particular depth depends on other factors. To balance at all in the density gradient, the submarine must be brought into stop trim for some depth at which buoyancy is stable, that is between the points A and B in Figure 1. The greater the change in buoyancy within the limits of stable buoyancy, the more easily will the submarine be trimmed correctly for balancing. Actually, submarines have been balanced in gradients in which the buoyancy was stable through only a range of 500 pounds. Since this is close to the limit of accuracy of trim adjustments, success depended somewhat on luck. It should, however, be quite easy to bring a submarine to balance in a gradient of 2,000 or 3,000 pounds range of stable buoyancy.

Where operation at a particular depth is at issue, the greater the buoyancy change per unit depth, the more easily is depth held since large changes in weight cause only small changes in depth On the other hand, a submarine balanced in a sharp density gradient is in greater danger of falling through than in one extending over greater depth, since in the former case it is given less warning by change in depth that its buoyancy is decreasing.

## 8.4 THE RATE OF SINKING IN UNSTABLE BUOYANCY

Much of the prejudice against balancing which previously existed arose from the belief that on sinking below the density gradient, a submarine would become heavy so rapidly that it was in danger of getting out of control. This was based in part on the known effect of compression in decreasing the buoyancy of a submarine as it went deeper. It was also based on the erroneous belief that the buoyancy of the water decreased below the "density layer." In order to test this hazard, experiments were made in which a balanced submarine was deliberately caused to sink through the density gradient by flooding in successive small quantities of ballast until it was no longer in stable buoyancy. When 500 or 1,000 pounds of ballast were flooded in while the submarine was balanced near the lower limit of the thermocline, it sank at a rate of about 2 feet per minute. When it reached the unstable water below the thermocline, its rate of fall increased rapidly, as recorded in Table 1.

TABLE 1. Rate of Sinking of Submarine When out of Trim.

| Amount heavy pounds | Rate of fall feet/minute |
|---|---|
| 500 | 3.3 |
| 1,000 | 6.6 |
| 3,100 | 30.0 |
| 12,000 | 50.0 |

Unless grossly out of trim, the submarine could easily be brought back into balance at the proper depth. Even when 3,100 pounds heavy and sinking 30 feet per minute, it was possible to pump out the excess ballast and bring a submarine into balance in the thermocline again. When 12,000 pounds heavy and falling 50 feet per minute the vessel was brought back into balance by blowing ballast from the negative tank which had been flooded. In neither case was it necessary to start the motors to regain control.

It was always possible to check the descent of the overweighted submarine and bring it back into the stable zone by use of motors and planes. The compensations which can be made in this way will be considered in the following chapter.

There appears to be no danger of a balanced submarine getting out of control on falling through a thermocline *provided constant watch is kept of its position* in the density layer. Warning will be given by the temperature recorded by the bathythermograph.

## 8.5 RUNNING IN BALANCE

A properly trimmed submarine may not only balance with motors stopped when conditions of stable buoyancy obtain, it may also proceed at low speeds without using the diving planes to control its depth. Experiments have indicated that this can be done at 1/3 speed, and that during the maneuver, turning the vessel with the rudder does not disturb its balance. At higher speeds, the submarine tended to ascend, as the result of lifting forces occasioned by the hull shape and its movement through the water. The critical speeds at which this occurs probably depends on the strength of the density gradient.

Even though the stability conditions are not used to control the depth, it is evident that a submarine operating in a density layer may be more easily kept at constant depth with the aid of the planes since each deviation from the desired depth sets up forces which tend to restore its position.

The planing forces which arise from the motion of a submarine and their relation to the static buoyancy forces are discussed in the following chapter.

## Chapter 9

# THE USE OF PLANING FORCES TO CONTROL DEPTH

When a submarine moves through the water, forces arise which act on the hull with a vertical component. These forces may overbalance the static buoyancy forces with which we have been concerned in the preceding chapters. They may enable a submarine to hold constant depth when out of trim or to change depth when trimmed for stable buoyancy. Three groups of forces may be distinguished:

1. Planing forces due to the hull form.
2. A vertical component of the propulsive force determined by the angle of the hull.
3. Planing forces due to the angle of the diving planes.

All of these forces increase with the speed of operation of the submarine.

### 9.1 FORCES DUE TO HULL FORM

A balanced submarine, which lies horizontal in the water (hull angle = 0), tends to rise when under way. The greater the speed the greater is the tendency to lose depth. If the submarine is running in balance in a density gradient the tendency to rise is counterbalanced by the decrease in buoyancy which develops as the depth changes. Consequently, a submarine may frequently run in balance at low speed with the diving planes held horizontally (at zero angle). The tendency for the submarine to rise becomes greater at higher speeds. The greater the change in density with depth, the less noticeable will this tendency be, and the higher the speed at which the submarine will hold depth without active control with the diving planes.

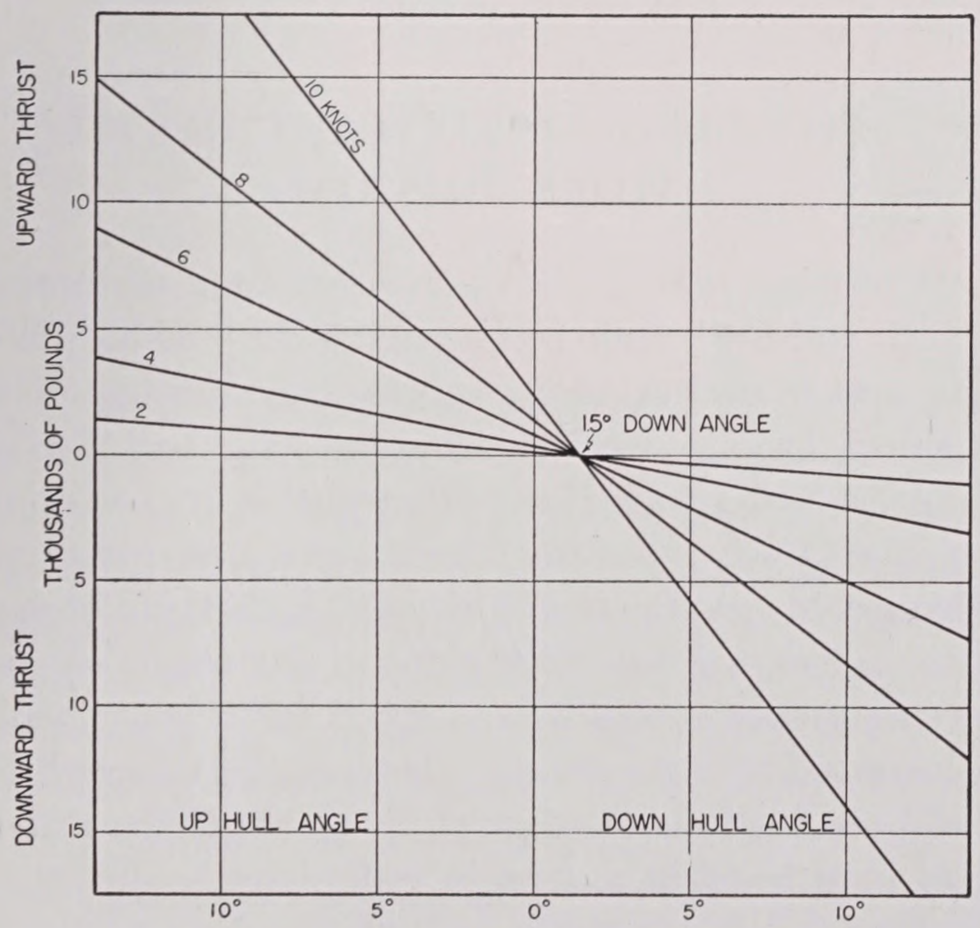


Figure 1. Vertical component of propeller thrust of a fleet-type submarine as a function of speed and of hull angle. It is assumed that the propeller shaft is inclined to the water line by 1.5 degrees.

The tendency of a submarine to rise as speed increases may be attributed in part to planing forces due to the form of the hull and superstructure. It is probable that the drag of the superstructure tends to cause the bow to rise and that the small "up-angles" of the hull which result contribute to the loss in depth. Furthermore the vertical component of the propeller thrust discussed below acts like an increasing buoyant force as speed is increased.[a]

### 9.2 VERTICAL COMPONENT OF THE PROPULSIVE FORCE ARISING FROM THE HULL ANGLE

The hull angle of a submerged submarine is measured relative to the normal water line of the vessel when surfaced. If the water line is horizontal, the hull angle is zero. If planing forces are neglected and it is assumed that the propulsive force is applied parallel to the water line, and at the center of resistance to forward motion, the vessel may be expected to move forward in the direction of the hull angle. If the hull is inclined the propulsive force will have a vertical component, proportional to the sine of the hull angle, which will cause the submarine to rise or sink as it moves forward. As a result small hull angles will cause a moving submarine to change depth rapidly in spite of opposing buoyancy forces.

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[a] In addition to the forces under discussion which arise from the forward motion of the submarine, other forces which throw it out of trim are set up when the vessel turns in the horizontal plane. These cause the submarine to become heavy overall and heavy aft. The effect amounts to 6,000 pounds lost buoyancy at a speed of 5 knots. It is thought to be due to a low pressure zone created beneath the unsymmetrical hull by its horizontal broadside motion. This effect can be compensated for by suitable use of the diving planes when turning.

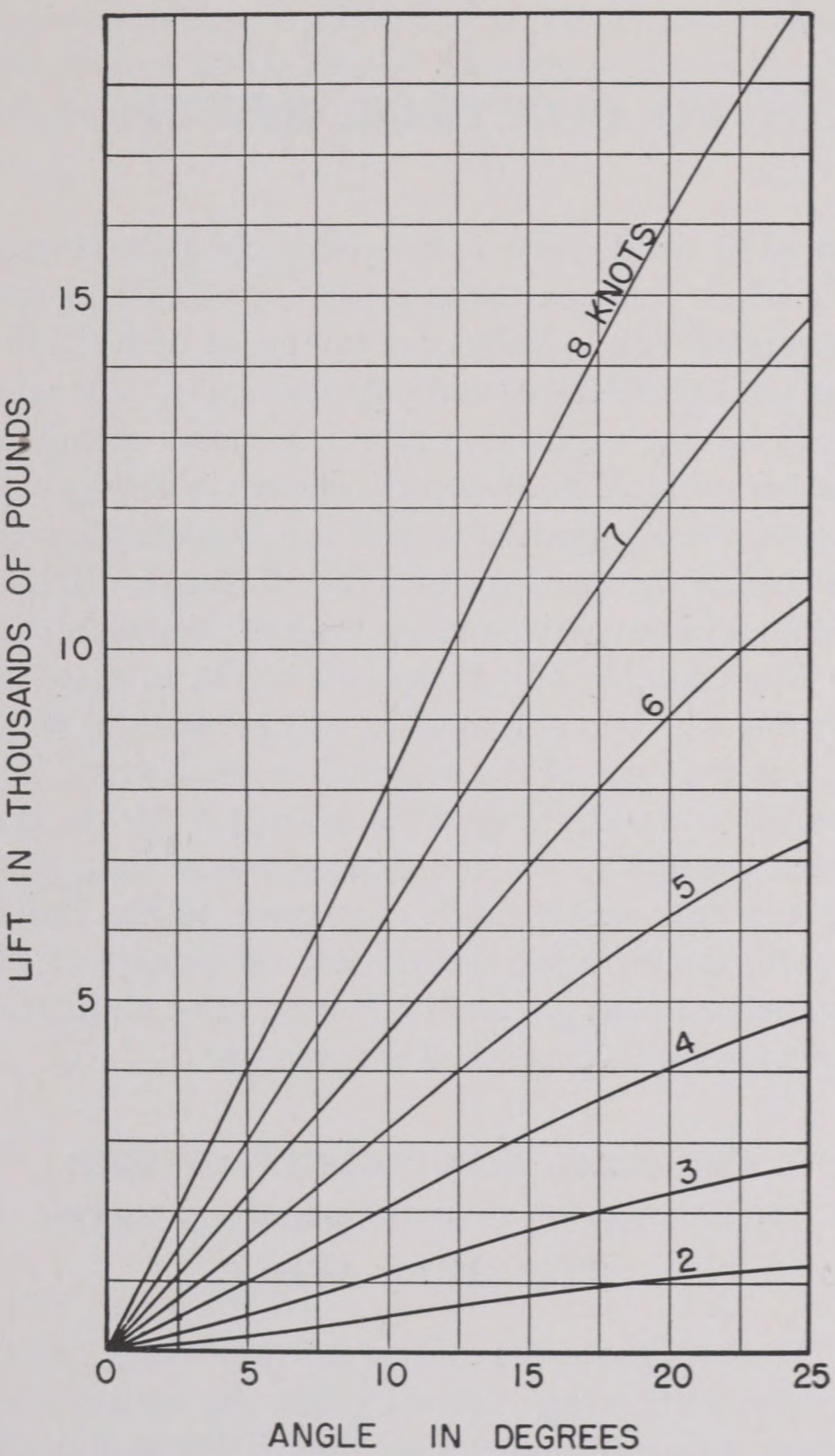


FIGURE 2. Vertical force developed by bow planes, assuming total area of 124 square feet, as function of their angle and the speed.

Actually the propeller shafts are usually inclined to the water line at an angle of about 1½ degrees. In consequence, if the hull angle is zero a small component of the propulsive force acts upward and tends to cause the vessel to rise as it moves forward unless counterbalanced by other vertical forces. The vertical component of the propulsive force is zero only when the hull assumes a down angle of 1½ degrees. The vertical component of the propulsive force at various hull angles and speeds is estimated to be as shown in Figure 1.

In addition, in most fleet-type submarines the thrust of the propellers acts on a point below the center of forward resistance. The thrust consequently causes the bow to tend to rise and to alter the hull angle in a way which also favors an upward movement of the vessel. In some of the more recent fleet-type submarines the propeller thrust acts approximately on the center of resistance and this effect is minimized.

## 9.3 PLANING FORCES DUE TO THE ANGLE OF THE DIVING PLANES

The vertical forces developed by the diving planes depend upon the angle of the planes and the speed of movement. The magnitude of these forces has been calculated, using the accepted rudder equations for bow planes of 124 square feet combined area, and is illustrated in Figure 2. The vertical force developed by the stern planes is about 20 per cent less.

When the bow and stern planes are adjusted so that their vertical moments are balanced, their combined force tends to cause the submarine to rise or sink without change in hull angle. When the vertical moments are not balanced the hull angle changes so that the submarine moves upward or downward as it is propelled forward.

In practice, one planesman adjusts the bow planes so as to bring the vessel to the desired depth and the other manipulates the stern planes to hold the vessel at the desired hull angle. In this way the vertical moments of the action of the bow and stern planes are approximately balanced and both contribute to the vertical movement of the vessel.

## 9.4 MAINTAINING CONSTANT DEPTH WHEN IN TRIM

A moving submarine when submerged maintains depth and hull angle by balancing the various planing and buoyancy forces against one another. The vertical forces which arise from movement all tend to increase with speed. If the submarine is in good trim, so that static buoyancy forces are not involved, changes in speed may not disturb the balance of vertical forces and no adjustment of the angles of the diving planes is required as speed increases. This is illustrated by data on the plane angles required to hold constant depth, secured by a submarine which had been brought to trim by balancing, as shown in Table 1.

If the submarine's hull angle is zero, relatively large forces must be developed by the diving planes to overcome the vertical components of the propeller thrust and the upward forces arising from the hull form. This leads to the employment of undesirably large plane angles. If the hull is given a slight downward inclination by increasing the angle of the stern planes the tendency to rise is counterbalanced by the vertical component of the propulsive force. The submarine will then move forward at constant depth without the use of the bow planes. The data recorded in Table 2 illustrate the angles of hull and stern planes required to hold constant depths at different speeds, when the bow plane angle is zero.

TABLE 1. Plane Angles Required to Hold a Balanced Submarine at Constant Depth at Various Speeds. USS CATFISH.

| Speed | Hull angle | Bow plane angle | Stern plane angle |
|---|---|---|---|
| 1/3 | 0° | 10° dive | 5° dive |
| 2/3 | 0° | 12° dive | 4° dive |
| Standard | 0° | 12° dive | 4° dive |
| Full | 0° | 10° dive | 4° dive |

TABLE 2. Hull Angle Required to Hold Constant Depth at Various Speeds Without Use of Bow Planes.

| Submarine | Speed | Hull Angle | Bow plane angle | Stern plane angle |
|---|---|---|---|---|
| CATFISH | 1/3 | 0.50° down | 0° | 7° dive |
| | 2/3 | 1.30° down | 0° | 9° dive |
| | Standard | 1.75° down | 0° | 7° dive |
| | Full | 2.50° down | 0° | 7° dive |
| CUTLASS | 1/3 | 1.50° down | 0° | 7° dive |
| | 2/3 | 1.50° down | 0° | 6° dive |
| | Standard | 1.40° down | 0° | 5° dive |
| | Full | 1.40° down | 0° | 6° dive |
| | Flank | 1.40° down | 0° | 6° dive |

The first of these tests indicate that the hull angle required to hold depth without the use of the bow planes increases with the speed. In the second test, however, the speed could be changed without much adjustment of the hull angle. In a number of tests made in the New London area the latter result was obtained also, it being found that speed could be changed without adjustment of the diving planes when the hull was at 2 to 2½ degrees down angle. The reason for the difference in behavior in the different tests is not understood. Many submariners are agreed, however, that their vessels are more easily controlled when trimmed to secure a small down angle of the hull.

## 9.5 MAINTAINING DEPTH CONTROL WHEN OUT OF TRIM

If the submarine is not in good trim, the forces arising from the diving planes and hull angle are employed to overcome the static buoyancy. These planing forces increase with speed; the buoyancy forces do not. Consequently, changes in speed require adjustment of the plane angles. Obviously less angle is required on the planes at higher speed to overcome a given buoyancy force. When the submarine is out of trim depth is more easily controlled at high speed.

In the study of the precision of ballast adjustments, discussed in Chapter 6, it was found that in 25 dives in which good static trims were not obtained because of high speed or otherwise, less ballast was shifted than was predicted to be required by the bathythermograph in all but one case. In three-quarters of the cases the ballast change was more than 3,000 pounds less than the prediction; in extreme cases it was 14,000 and 16,000 pounds less.

A number of experiments have been made to determine the magnitude of the buoyancy force which may be overcome by the forces arising from the hull and plane angles at different speeds. The procedure is to bring the submarine to trim at low speed and then by flooding in or pumping out ballast to determine how much of a weight change may be made before operation of the diving planes at maximum

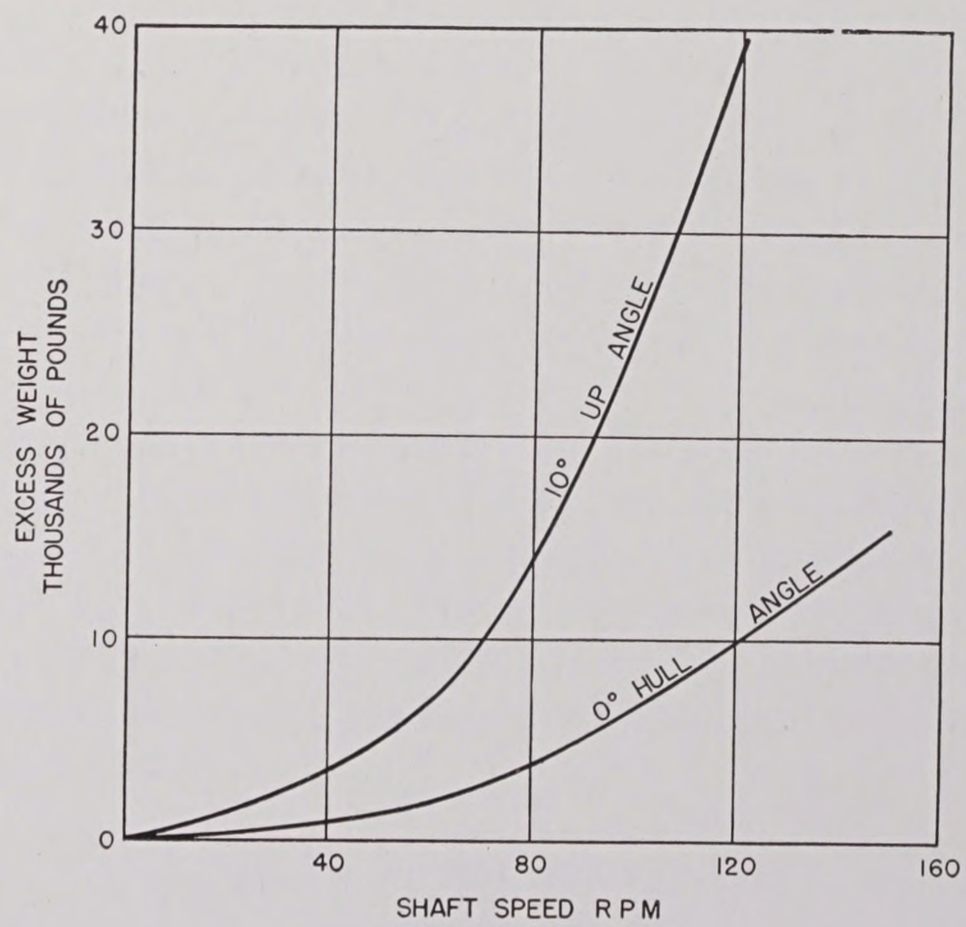


FIGURE 3. Effect of speed and hull angle in counterbalancing excess weight of a submerged fleet-type submarine, so as to permit control of depth of operation.

angles fails to maintain the depth. The speed is then increased and the test repeated by taking on or discharging more ballast. Some typical results, showing the maximum buoyancy change which can be compensated for under various conditions, are given in Table 3 and in Figure 3.

TABLE 3. Maximum Buoyancy Change Which Can Be Compensated for by Planing Forces at Different Speeds.

| Submarine | Speed | Bow plane angle | Stern plane angle | Hull angle | Maximum buoyancy compensation (pounds) |
|---|---|---|---|---|---|
| COBIA | 1/3 | — | — | 0° | 2,000 |
| | 2/3 | — | — | 0° | 11,000 |
| CATFISH | 1/3 | 25° dive | 0° | 0° | 1,200 |
| | 1/3 | 25° dive | 7° rise | 1° | 4,000 |
| | 2/3 | 25° dive | — | 1° | 8,000 |
| PERCH | 1/3 | — | — | 0° | 2,000 |
| | 2/3 | — | — | 0° | 5,000 |
| | Standard | — | — | 0° | 9,000 |
| | 1/3 | — | — | 10° | 7,000 |
| | 2/3 | — | — | 10° | 14,000 |
| | Standard | — | — | 10° | 38,000 |

It is evident that at high speed and with large hull angles, buoyancy forces can be overcome which are greater than any likely to be encountered as the result of the natural variations in the density of sea water. Under conditions of emergency, or as a temporary expedient in penetrating density layers, advantage may be taken of this fact. However, it is usually undesirable to maintain high speed when submerged for very long, because of the drain on the batteries and for tactical reasons. Consequently, the importance of keeping a submarine in good trim is not decreased by the additional control of buoyancy which may be had by taking advantage of the planing forces.

The various forces which determine the behavior of the moving submarine are evidently complex and great skill is required in operating the vessel to keep them in the most effective balance. A submarine might be so designed that it could be operated without using needlessly large plane adjustments to counterbalance the vertical forces which arise from the hull form, and to keep it at a proper hull angle. It is evident that present submarines depart widely from this ideal and also that the most effective combinations of hull angle, plane angles, and speed are not thoroughly understood. It is believed that a systematic study of the factors controlling the motion of the submerged submarine would not only lead to valuable information on how to operate the vessel most effectively, and thus supplement the skill which is acquired only by long experience, but also might serve to establish criteria for the design of more handy vessels.

## Chapter 10

# THE USES OF THE SUBMARINE BATHYTHERMOGRAPH IN OPERATIONS

THE CHANCE of success of any maneuver by a war vessel depends on the speed, certainty, and ease with which the operation can be carried out; the latter is particularly important in an emergency.

### 10.1 COMING TO TRIM AT A NEW DEPTH

The submarine bathythermograph[a] has earned a place in the control room if only because it reduces the uncertainty of ballast adjustments whenever the submarine changes depth. Prior to its introduction diving operations resembled somewhat the game of blindman's buff in which the diving officer tried to cope with forces which he could not anticipate and could only vaguely detect by his feel for the state of trim of his vessel. He was aided only by an instrument known in the Service as "the seat of his pants." The value of the newer device is attested by the following extracts from patrol reports:

> "Many density layers were encountered in this area particularly off Shiono Misaki and Daio Saki. . . . In each case the layer necessitated much flooding in to get down and pumping out to get back up. The bathythermograph predicted the necessary procedure nearly every time. This is a most valuable instrument but should be relocated in the Control Room where it can be of great assistance to the diving officer."
>
> "Density layers were found on both the east and west sides of Palau varying in depth from 150 feet to 300 feet. We checked the bathythermograph on each deep submergence for information of the Diving Officer which enabled him to adjust his trim so that during search following each attack while we were deep he never had to pump, blow or increase speed to maintain depth."

The disadvantage of delays encountered in coming to trim during evasion is very real, since the time is prolonged during which the noisy operation of the pumps and propulsive machinery is required. This is evidenced by the following extracts of patrol reports from submarines which were not equipped with bathythermographs:

> "In the South China Sea . . . while going deep to avoid depth-charge attack, it was necessary to flood in 10,000 pounds to remain at 240 feet and not come up, and standard speed had to be used until additional water had been taken aboard."

> "A density layer was encountered at about 275 feet. Below this depth our propeller beats must have been lost to enemy A/S vessels though we could still hear their propellers and their pinging. Any unusual noises, however, such as blowing or pumping were immediately picked up by them and drastic action followed."

Delay is not only disadvantageous in evasion, it may be important in more ways than one when resuming attack. Thus:

> "Density layers were experienced twice near Truk. On both occasions it was necessary to pump out 3,000 to 5,000 pounds to climb at 2/3 speed. Both times this occasioned considerable delay and no end of irritation to the commanding officer who was anxious to get a look."

Since the auxiliary ballast pumps can discharge only one or two thousand pounds per minute, depending on the depth, the delays in handling the large amounts of ballast mentioned in these reports were considerable and well worth keeping at a minimum.

The intelligent use of the BT can save much time in coming to trim. Most submarine commanders make an exploratory dive daily while on patrol to obtain information on the density conditions in the water in which they are operating. Some even make such a dive immediately before an attack, if conditions permit, so as to be acquainted with the situation which will be encountered when time comes to take evasive action. Ballast may then be shifted as soon as the submarine begins to descend and only small adjustments will be required after the chosen depth is reached.

Even if an exploratory dive has not been made previously, the record made during descent gives information of the buoyancy conditions being encountered long before they make an effect on the progress of the submarine, since when at speed the submarine remains under control when several thousand pounds out of trim.

### 10.2 SELECTION OF DEPTH OF OPERATION

Except when operating at periscope depth, the *exact* depth at which a submarine is held is usually

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[a] See footnote a, Chapter 1.

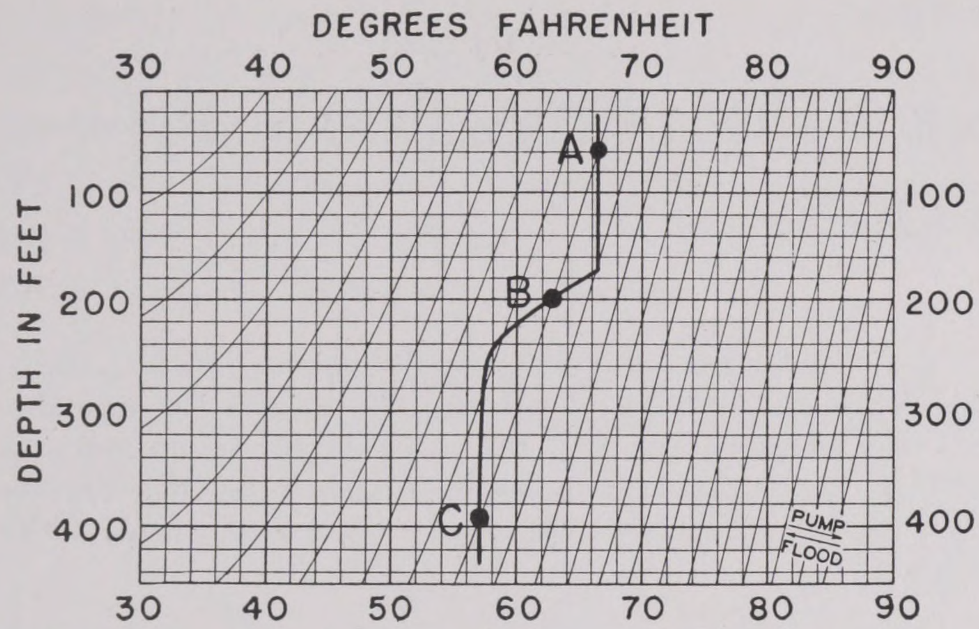


FIGURE 1. Temperature trace showing condition when a submarine in trim at depth *A* will also be in trim at the greater depths *B* and *C*.

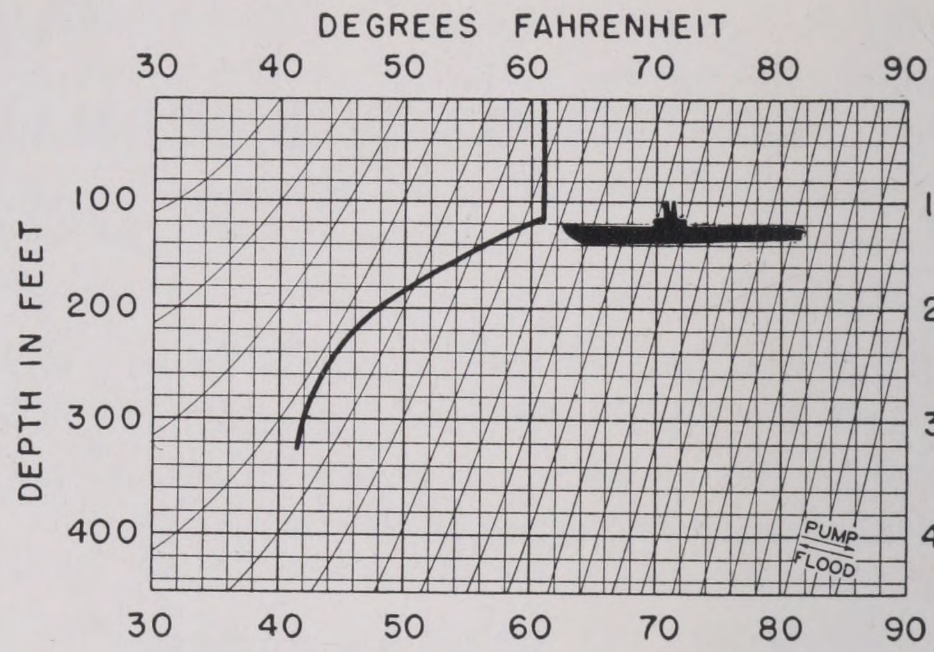


FIGURE 2. Temperature trace illustrating the depth at which a submarine may balance while using topside listening gear to best advantage.

not tactically important. A knowledge of the density distribution in the water will frequently permit a level to be selected which is advantageous for efficient operation.

If a strong density gradient is present there is usually one, and sometimes two deeper levels at which the buoyancy conditions are the same as at periscope depth. If a submarine in trim at periscope depth is taken to these levels with the diving planes, it can level off and come to trim again without any change in ballast. If the level selected is one of stable buoyancy, it is not even necessary to guide the submarine to the exact depth; if allowed to do so it will find its own level of good trim under the action of the forces which determine stability.

The depths at which a submarine in trim at periscope depth will also be in trim on deeper submergence are those where the isoballast line which passes through the temperature trace at periscope depth also crosses the trace at greater depths. Thus, in Figure 1, a submarine in trim at *A* will also be in trim at *B* and *C*. Buoyancy is stable at *B* and a submarine starting to sink from A or brought to any position near B under power, will tend to come to the depth of *B* as the result of the buoyancy forces. If the planes and power are used to penetrate the density layer to reach the depth of *C*, the submarine will again be in trim.

The advantage of leveling off at the depth, *B*, at which trim is the same as at periscope depth is not limited to the ease of silent descent. It also puts the submarine in a position to resume aggressive action at periscope depth without delays required by ballast adjustment.

Under depth charge attack some advantage is probably gained by going below a strong density gradient since a well placed charge may tend to "blow" the submarine to the surface. The decreased buoyancy of the gradient will tend to counteract the upward movement of the vessel and may prevent its broaching. This is, of course, only one of a number of reasons why submarines go deep in evasive maneuvers.

## 10.3 ADVANTAGES OF OPERATING IN A DENSITY LAYER

The BT shows the depths at which a submarine will encounter conditions of stable buoyancy. At such levels depth control at any speed is easier since the submarine tends to hold its depth and the diving officer and planesmen are under less strain. At low speeds the submarine will run in balance, holding its depth without use of the diving planes and thus eliminating any possible sound from that source. This is advantageous if the submarine wishes to maneuver at creeping speed near the surface in a position ready to initiate or resume attack. In deep evasion it is less important since the suppression of cavitation sound at greater depths makes it permissible to use higher speeds without danger of detection by listening devices.

When operating in a density layer, the submarine will tend to seek the depth at which it is in trim. If trim is imperfect, or if the depth of the density gradient is changing as the result of internal waves, the vessel will tend to rise or sink slowly. If allowed to do so, it will soon find its proper level. Consequently, when operating under stable conditions, it is much better to let the submarine find the level for which it is trimmed than to fight the buoyancy forces with the planes or to attempt to correct them by ballast adjustment. It has been the practice to operate submarines at a rigidly controlled depth, quite irrespective of the necessity. Actually, it is only at periscope depth that exact depth control is usually necessary. When running in a density layer at greater depths, the aim should be to keep the submarine in water of uniform temperature, where it will remain in trim. When a density layer is present an understanding of the situation can save much noise and effort.

Balancing in a density layer with motors stopped is not favored during evasive action, since there is danger of being caught dead in the water by an attacking escort. There are, however, several situations in which balancing may be used to advantage.

In listening for enemy vessels the quieter the submarine the greater the range over which their presence may be detected. By balancing at the very top of a temperature gradient, in a position where the topside sonic listening gear is above the gradient and is surrounded by isothermal water, the listening ranges will be substantially longer than those obtained at even slowest speed. (See Figure 2.) When listening conditions are good a submarine may cover a greater area by this procedure than by sweeping a narrower path while moving through the water.

When forced to remain submerged for long periods, there is danger that the batteries will become exhausted, necessitating a return to the surface. If a sufficient density gradient is present, a submarine balanced in it will use very little power while waiting for an opportunity to return to the surface.

In an emergency when it is necessary to stop the motors for repairs, balancing on a strong density layer may permit the submarine to avoid surfacing. An impressive instance of the use of this maneuver is given in the following extract from a patrol report:

> "At 230-foot depth there was a definite heavy layer that was used to advantage when the main induction was flooded. It carried us for several hours . . . when as much as 5 or 6 thousand pounds heavy. It apparently had an effect on sound conditions and prevented the DD from any effective sound work as we were making considerable noise for a period of over an hour while he was nearby and we were below the inversion."

## 10.4 MAINTAINING PERISCOPE DEPTH

Sudden fluctuations in density sometimes disturb the trim of submarines running at periscope depth. The vessel may unexpectedly sink or rise from the desired depth causing the periscope to be submerged or to become dangerously visible.

A submarine patrolling off Honshu, north of Tokyo, reports:

> "Inshore the water was highly stratified with violent horizontal as well as vertical temperature gradients. Depth control was always a problem. . . . "

Another report from off Tokyo emphasizes the relation of these disturbances to temperature fluctuations.

> "During normal submerged running at 60 feet temperature changes had a marked influence on over-all trim, varying trim approximately 800 pounds per degree change in temperature. In all cases, however, this figure did not hold true, due perhaps to various changes in the density of sea water caused by other factors."

This vessel had a BT and evidently found it useful to anticipate the required ballast compensations. The working rule proposed is correct for water of about 70 F. When the rule failed to hold, it is quite probable that the BT thermal element did not record accurately the changes in temperature of the water surrounding the hull, since it is located some 15 feet above the center of buoyancy and may have projected above the thermocline at times.

The use of the BT in such conditions is again suggested by the experience of a submarine during a shakedown cruise in the Gulf of Maine.

> "It was impossible to obtain a final trim at periscope depth for the three days in this area because of the extremely erratic changes in the water temperature as shown on the bathythermograph records. The temperature at 65 feet would often change eight degrees in a minute's time, then in about five minutes change just as erratically in the opposite direction. One of the junior officers found that if he watched these changes and pumped or flooded accordingly, he could maintain trim without having to lose it first. In other words, the bathythermograph told him he was going to lose his trim a short time before he actually lost it."

Disturbances of this sort are frequently attributed to "water pockets." In the cases described they are probably due to *internal waves* which distort the level of the density gradient found in the thermocline. A submarine at constant depth cuts through these waves becoming lighter as it penetrates a crest and heavier as it crosses a trough.

Internal waves of this character only make themselves felt when the vessel is in a density layer. They do not make trouble unless the density layer occurs at periscope depth, since this is the only level where exact depth control is important.

## 10.5 THE DEPENDENCE TO BE PLACED ON BATHYTHERMOGRAPH PREDICTIONS

It needs to be emphasized that the BT is intended to assist the diving officer in conducting his operations, but that it cannot do his work for him. Its indications are predictions of the approximate buoyancy conditions he will encounter or is encountering. It should be remembered that the instrument, in its present form, does not take salinity gradients into account, that the water conditions are subject to change from time to time and place to place, that the recording mechanism is influenced by the water at only one point, and that frequently remote from the center of buoyancy, and that a submarine is often somewhat out of trim at the start of a dive. Consequently, the BT does not give an exact indication. Its predictions have proved useful in achieving approximate trim at new levels, but the diving officer must still exercise his judgment and skill in the final adjustment of buoyancy.

## Chapter 11

# SUBMARINE SUPPLEMENTS TO THE SAILING DIRECTIONS

THE SAILING Directions issued by the Hydrographic Office, together with the Coast Pilots published by the U. S. Coast and Geodetic Survey, give an account of the local conditions which affect the navigation of surface ships throughout the world. In addition to a description of coastal conditions, harbors, port facilities, and aids and hazards to navigation, they summarize the winds, weather, sea conditions, and currents which are to be expected in the various areas of the ocean. In short, they attempt to provide the navigator with a background of information on what he is to expect in the course of his voyage and thus forewarn him and supplement the observations which he may make as he proceeds.

The submarine supplements are intended to extend such information in directions which are of peculiar importance to submarine operations. Thus they give an account of the hydrographic conditions which influence the diving operations of submarines, and the characteristics of the water and sea bottom which control the length of sound ranges in various locations. Since submarines are dependent on dead reckoning during submergence, the supplements present when feasible more detailed information on currents than is found in the Sailing Directions themselves.

The first supplements were prepared at a time when bathythermographs had not yet become generally available and some attempt was made to provide information on buoyancy conditions which might actually be helpful in diving a submarine. Now that bathythermographs are in general use this need is not so great except in the case of breakdown. However, information is provided on the presence and strength of salinity gradients which is of immediate use to submarines equipped with bathythermographs since it indicates when the predictions may become unreliable and gives a general estimate of the correction which should be applied on account of the salinity gradient.

A second way in which the supplements may be useful to the submarine on patrol is in showing whether the conditions presently encountered are liable to change, either because the area of operation is one of variable hydrography, or because the vessel's course is taking it into a region where the situation is different. Knowledge of this sort should determine the frequency with which exploratory dives are made. It is particularly important that a submarine running on the surface should be aware of changing buoyancy conditions since difficulty may be experienced in coming to trim on submerging if the density of the water at periscope depth changes in the course of the run.

In addition to these immediate uses the information in the supplements has an intangible but very real value in giving the submariner an advance picture of the conditions he is likely to meet during a patrol and thereby preparing him for difficulties. The supplement thus takes the place of the man who has been there before.

The supplements contain information which should also be of great value in strategic planning. The information supplied concerning sound ranging conditions make it possible to distribute available forces in such a way as to take advantage of the immunity from detection during evasion which is afforded by favorable temperature gradients. There is some indication that the Germans took advantage of this possibility in planning their submarine campaigns in the Atlantic and very good evidence that our own antisubmarine operations were greatly handicapped in areas where sound conditions were favorable to the German submarines. Even within the limits of an assigned patrol area, local conditions such as the character of the bottom may permit a submarine to choose the exact position of operation so as to be at an advantage.

## 11.1 AREAS COVERED BY THE SUPPLEMENTS

The only area in the Atlantic which has been covered by a submarine supplement is the Bay of Biscay.[1] A preliminary supplement on the eastern North Atlantic was prepared for the National Defense Re-

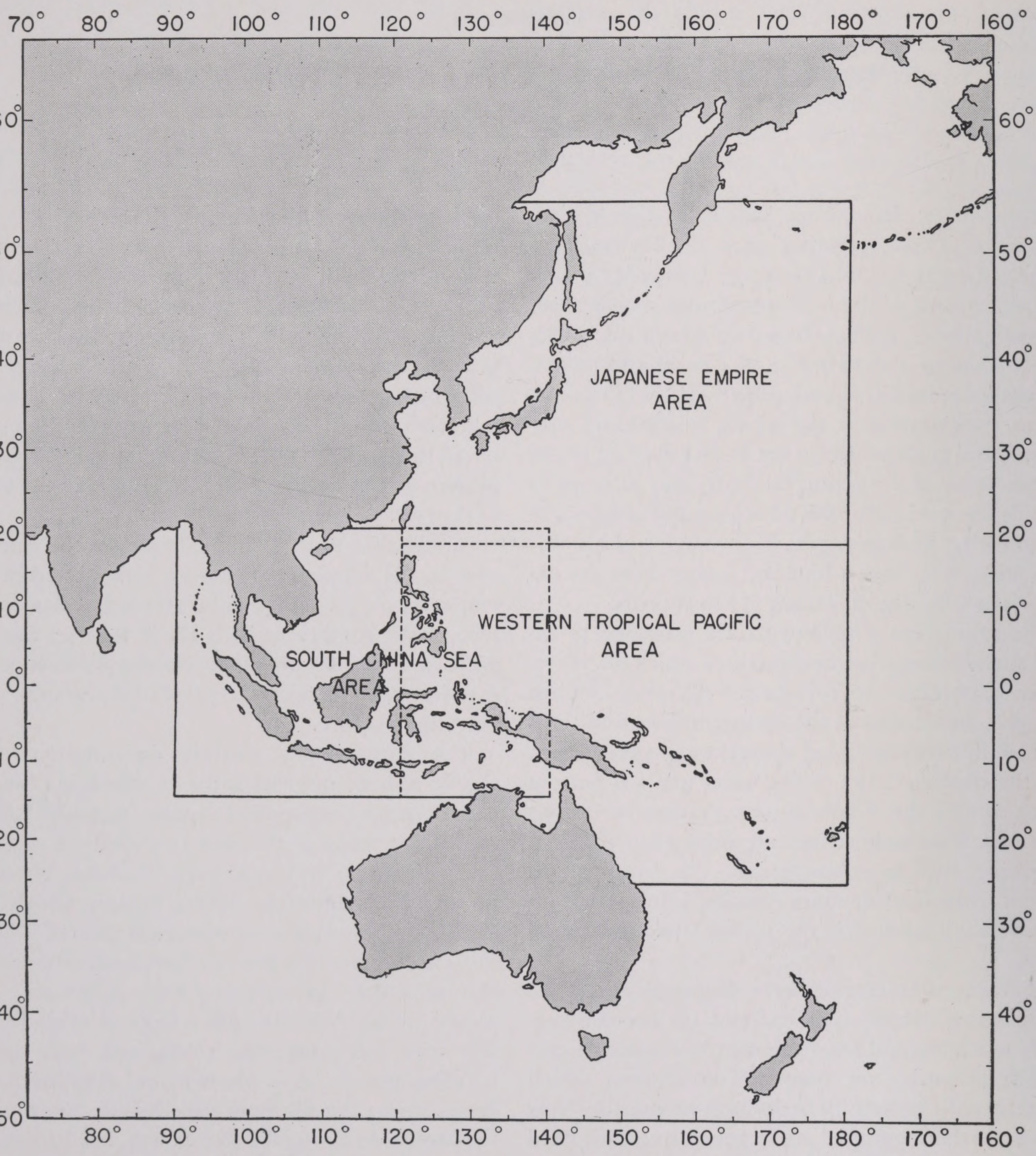


FIGURE 1. Chart showing the areas in the Pacific covered by the submarine supplements.

search Committee, but was not published due to changing war conditions.[2] Supplements[a] covering conditions for the entire year have been published for three areas in the Pacific where American submarines have undertaken extensive operations, namely, the South China Sea, the western tropical Pacific, and the area surrounding the Japanese Empire.[3–5] These areas overlap slightly. (See Figure 1.)

It seems highly desirable that additional supplements be prepared for all the oceanic areas of the world. There is immediate need for supplements covering the various training areas in the United States, such as off Portsmouth, New London, Key West, San Diego, and the Panama Canal. These would not only serve to acquaint men in training

[a] Preliminary submarine supplements were published for some of the seasons in these areas. These are listed in the bibliography.

with the uses of the supplements, but would also give them a better understanding of the conditions which they encounter during their training. In addition, in conducting tests it is frequently important to select locations where particular sound or buoyancy conditions occur. Much time would be saved and better tests would result if such information on local hydrography were conveniently available.

## 11.2 INFORMATION SUPPLIED

Under the heading *Subsurface Climate* the general hydrographic conditions which influence diving and sound transmission in the various natural areas are described. Typical BT records and extracts from patrol reports from the area serve as illustrations. The Japanese Empire Area is divided into ten subareas for this purpose; in the South China Sea Area and the Western Tropical Pacific Area, the subsurface climate is discussed as a whole.

Under *Subsurface Forecasting* some account is given of such factors as the weather, currents, and the run-off from land, which may enable changes in the situation to be predicted. Charts are included showing the character of the bottom or giving an index to the available bottom sediment charts of the area. Information on the transparency of the water is supplied where available. The most useful information, however, is given in a series of charts which show the average conditions for all seasons of the year which affect certain basic operations. The charts in the Supplement for the Japanese Empire Area cover the following features.

### 11.2.1 Surface Current Charts

Streamlines

These charts show the average resultant direction and velocity of the major surface currents. They do not include tidal current. (See Figure 2.)

Surface Currents — Roses

The amount of time the currents flow in different directions and at different speeds are shown. (See Figure 3.)

### 11.2.2 Buoyancy Charts

The data on all buoyancy charts are given for a submarine having a submerged displacement of 2,400 tons and a compression of 2,000 pounds per 100 feet, and are in terms of pounds of ballast to be pumped or flooded.

Buoyancy Change Due to Salinity Gradient

These charts show the change in buoyancy due to the salinity gradient between periscope depth and some stated level of deep submergence (300 or 450 feet). They may be used to learn whether the BT prediction will be dependable or whether an allowance should be made for the effect of salinity in predicting ballast change. The buoyancy corrections are given in terms of ballast to be flooded, and are either to be added to the amount flooded, or subtracted from the amount to be pumped, as predicted by the bathythermograph. (See Figure 4.)

Buoyancy Change Due to Density Gradient

These show average ballast changes due to both temperature and salinity gradients between periscope depth and some stated depth suitable for deep submergence (300 or 450 feet). They show whether strong density layers are likely to be encountered and indicate the total ballast change which may be required in deep submergence. (See Figure 5.)

Sharpness of Density Layer

The maximum sharpness of the density layer and its approximate depth are shown. The purpose of this chart is to show the depths at which density layers exist within the range of submarine operations and the security of balancing within these layers. (See Figure 6.)

Size and Thickness of the Density Layer, August

This chart shows the depth to the top and the depth to the bottom of the main density layer, and the size of the layer in terms of amount of ballast which must be flooded to penetrate the layer. It supplements the preceding one in showing the existence of balancing conditions and the range of depth through which such conditions can be expected. It applies only to the month of August when the most noticeable gradients occur. (See Figure 7.)

### 11.2.3 Sonar Range Charts

Periscope Depth, Echo Range, and Effect of Wind

These charts show the frequency in which maximum echo ranges at periscope depth are less than

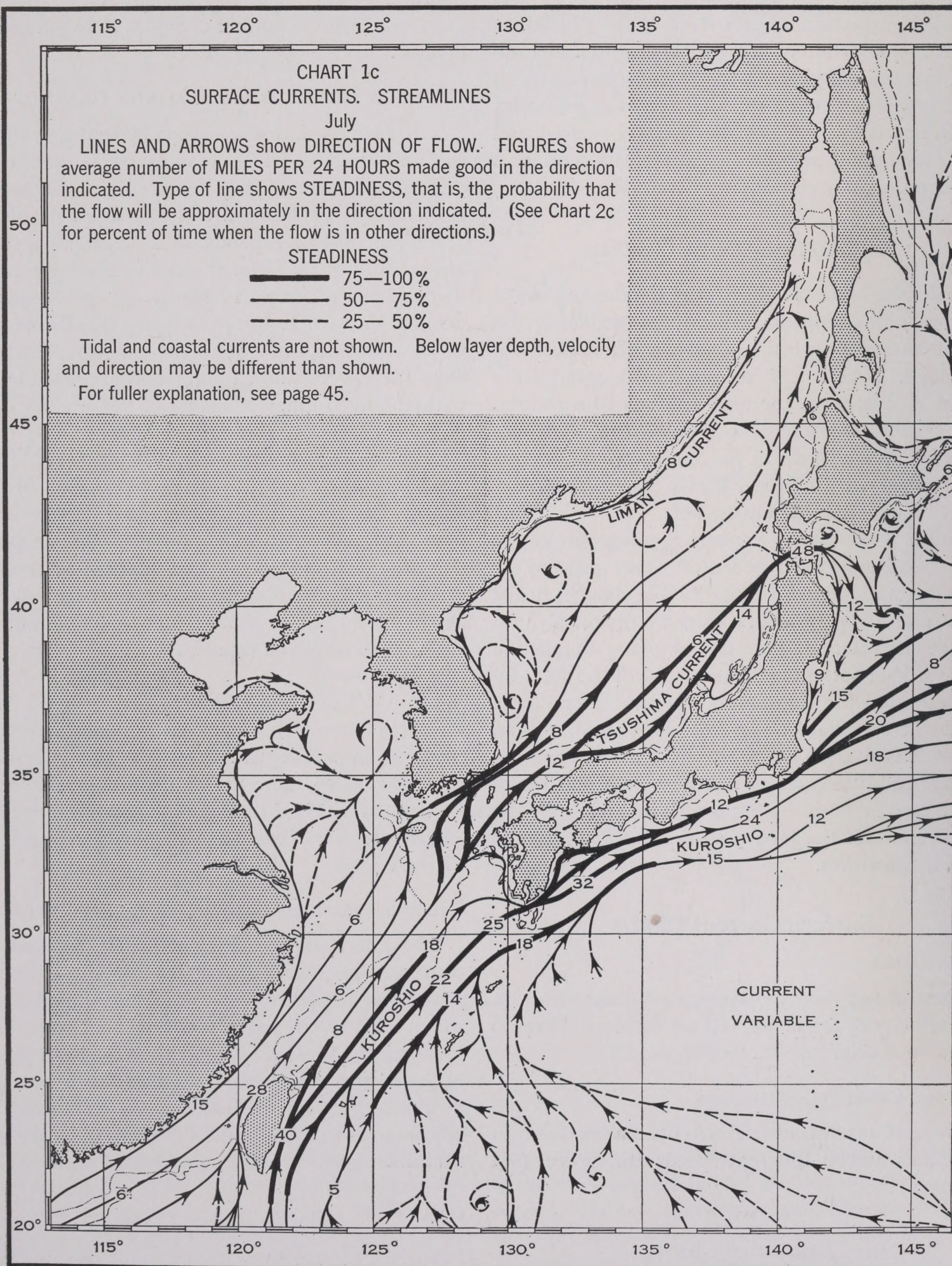


FIGURE 2. A part of Chart 1c from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating surface currents as streamlines.

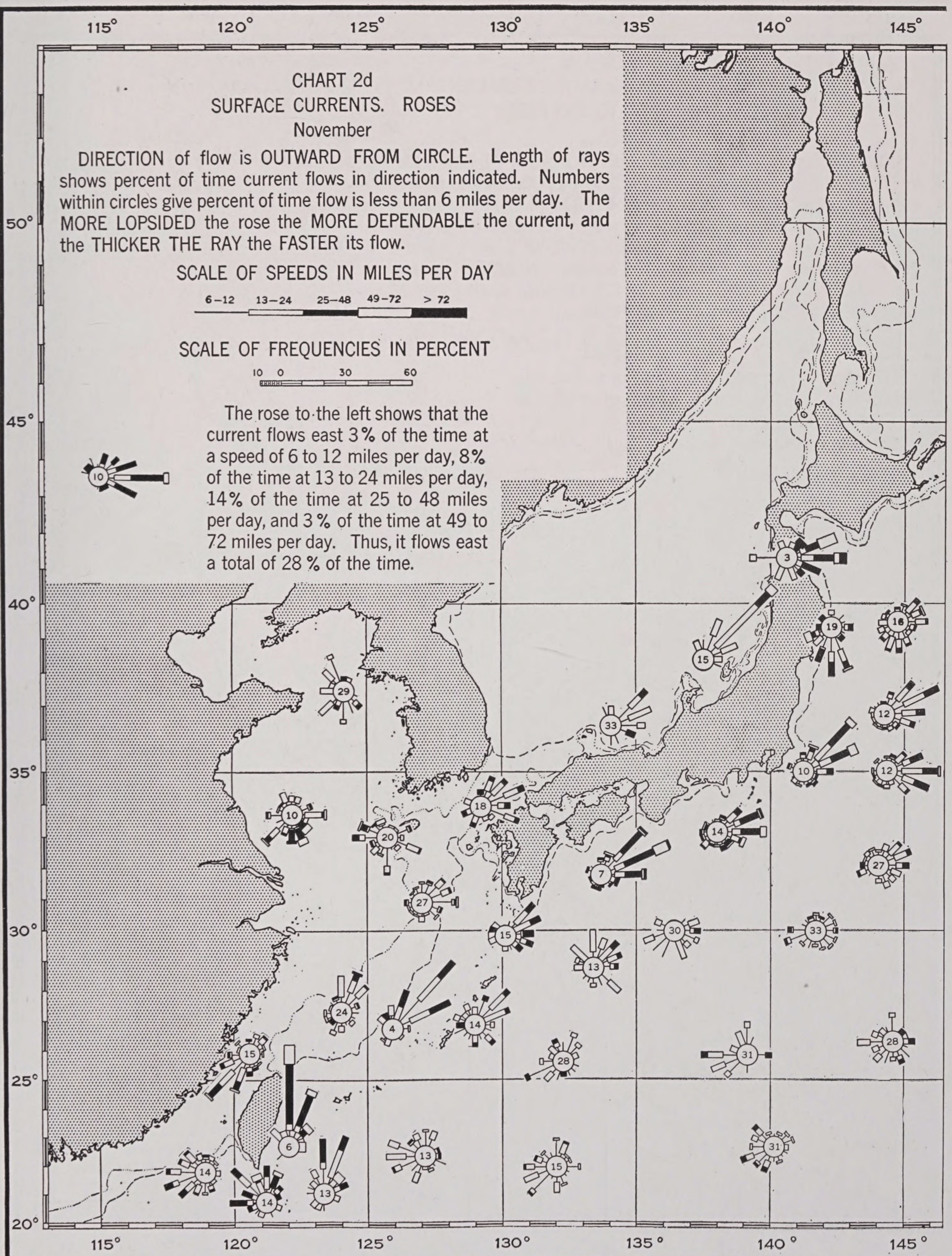


Figure 3. A part of Chart 2d from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating surface currents by means of roses.

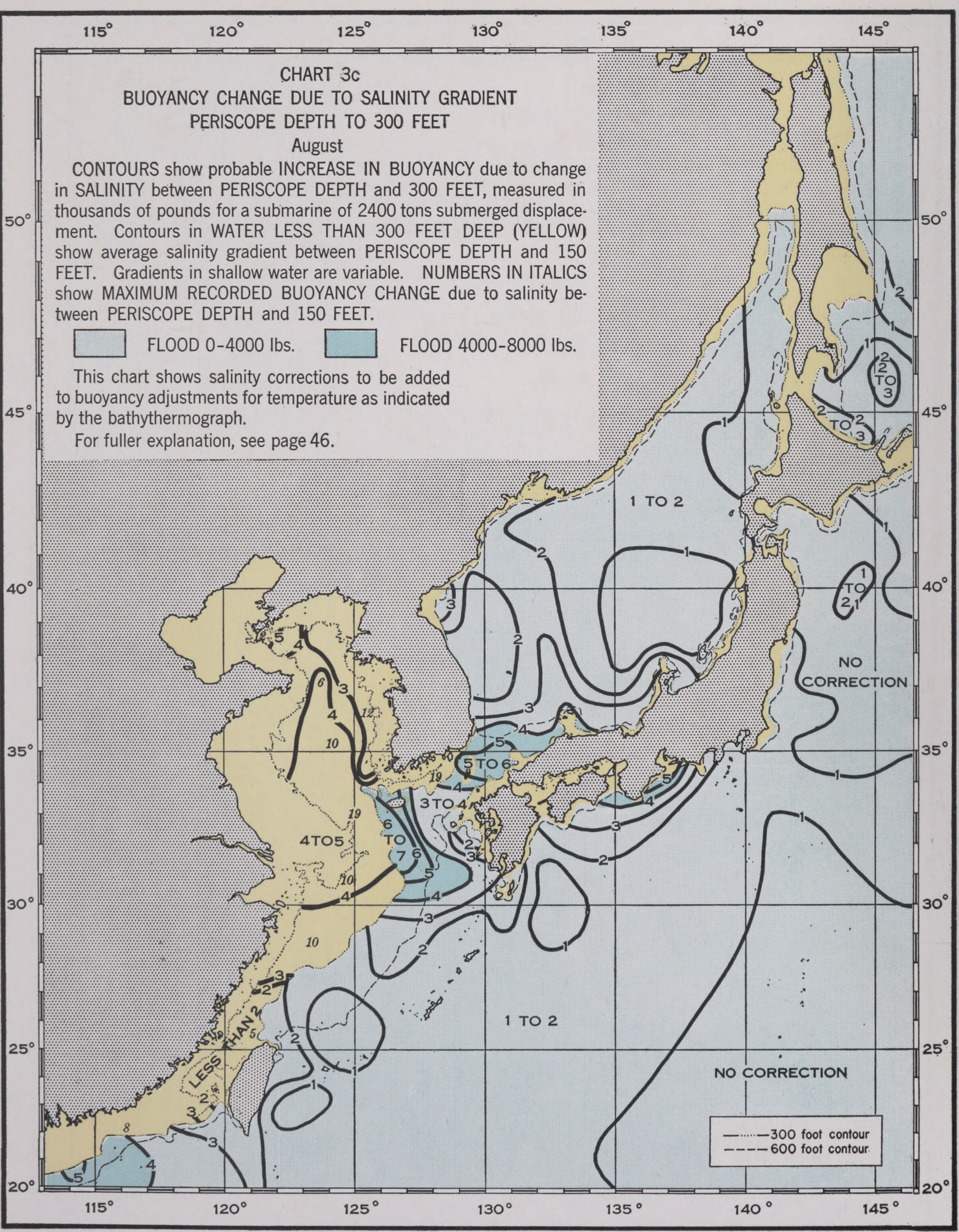


FIGURE 4. Chart 3c from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating buoyancy change due to salinity gradient between periscope depth and 300 feet.

[redacted]

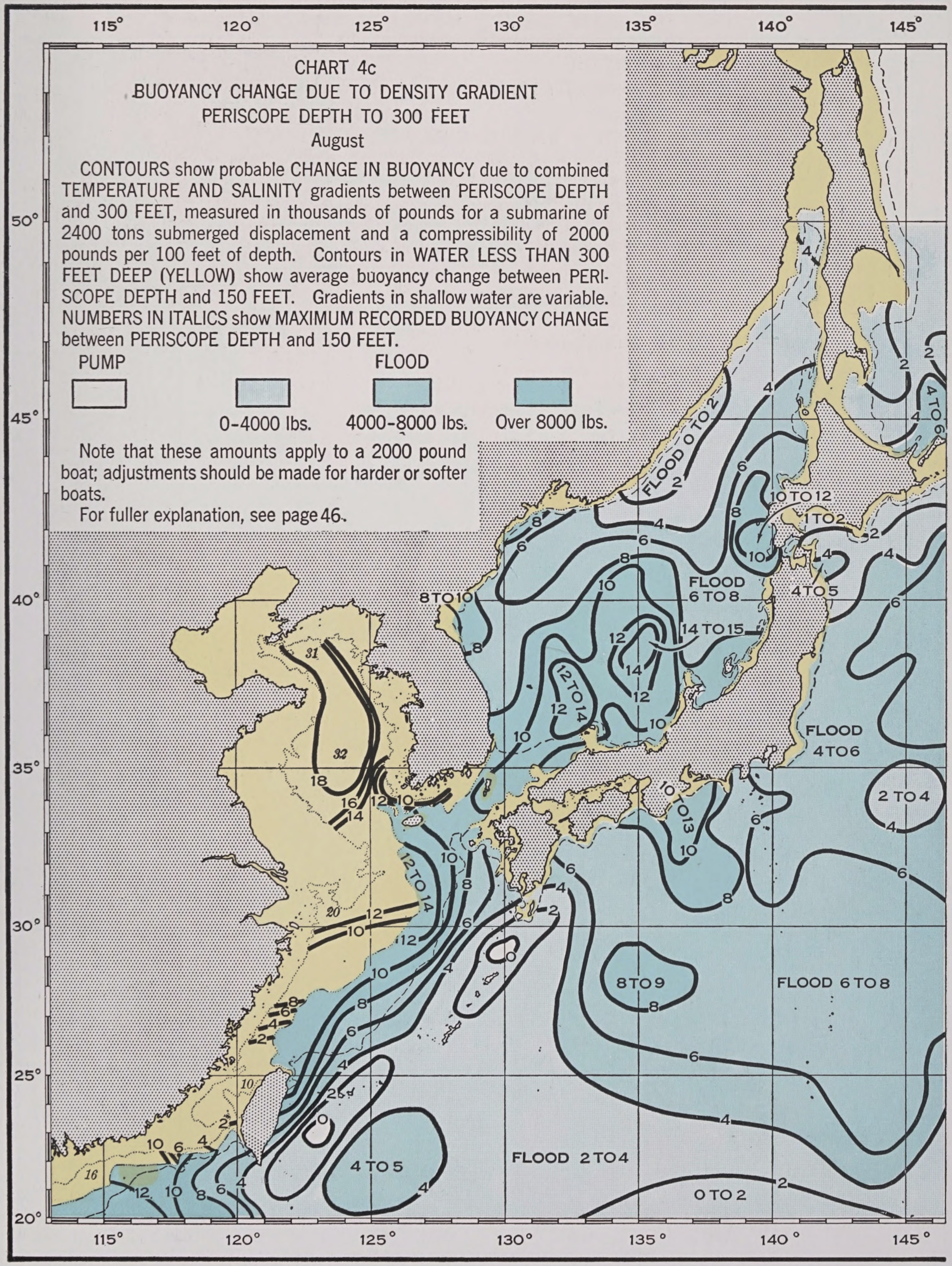


Figure 5. A part of Chart 4c from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating buoyancy change due to density gradient between periscope depth and 300 feet.

[redacted]

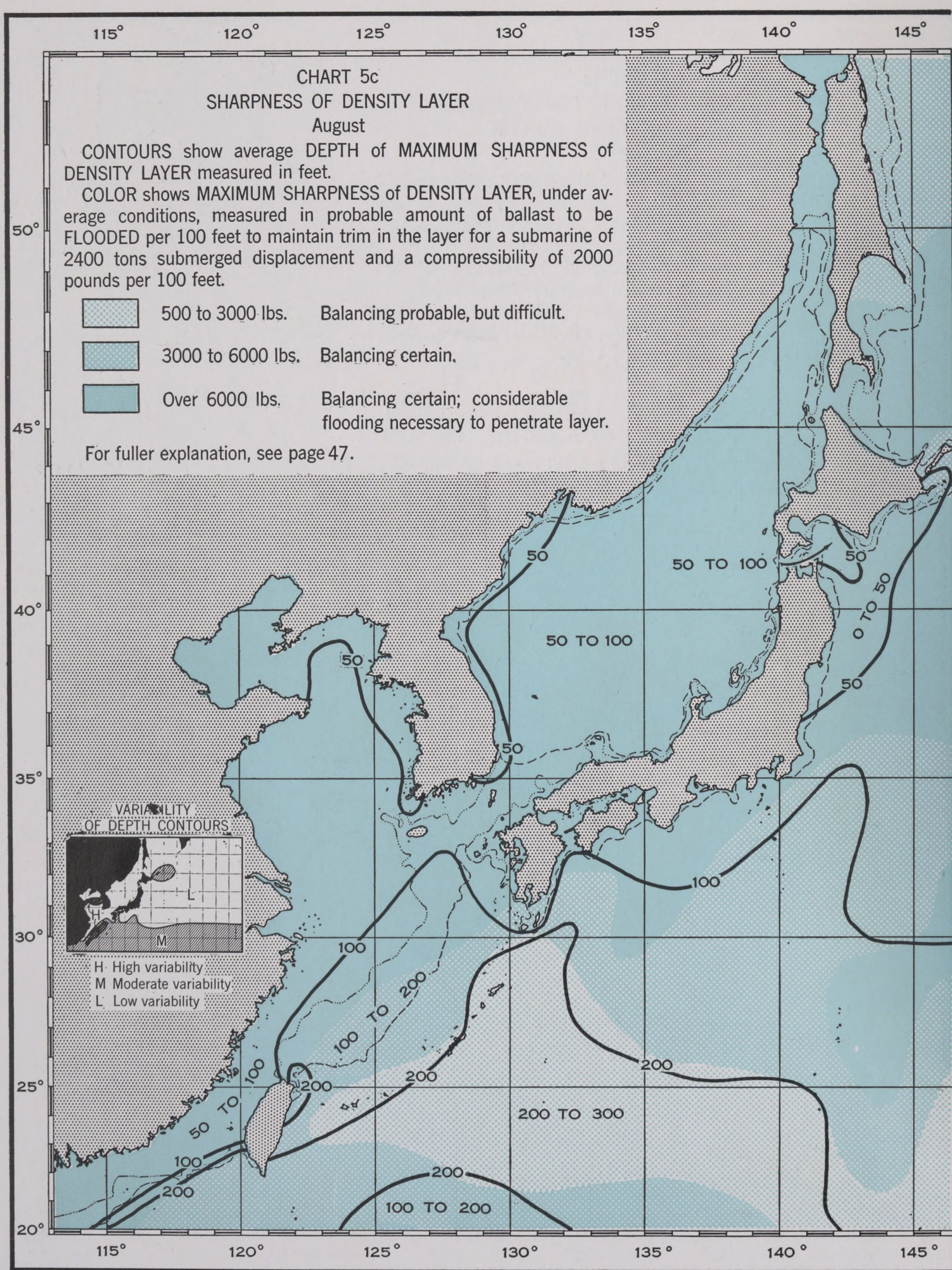


FIGURE 6. A part of Chart 5c from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating sharpness of the density layer.

[redacted]

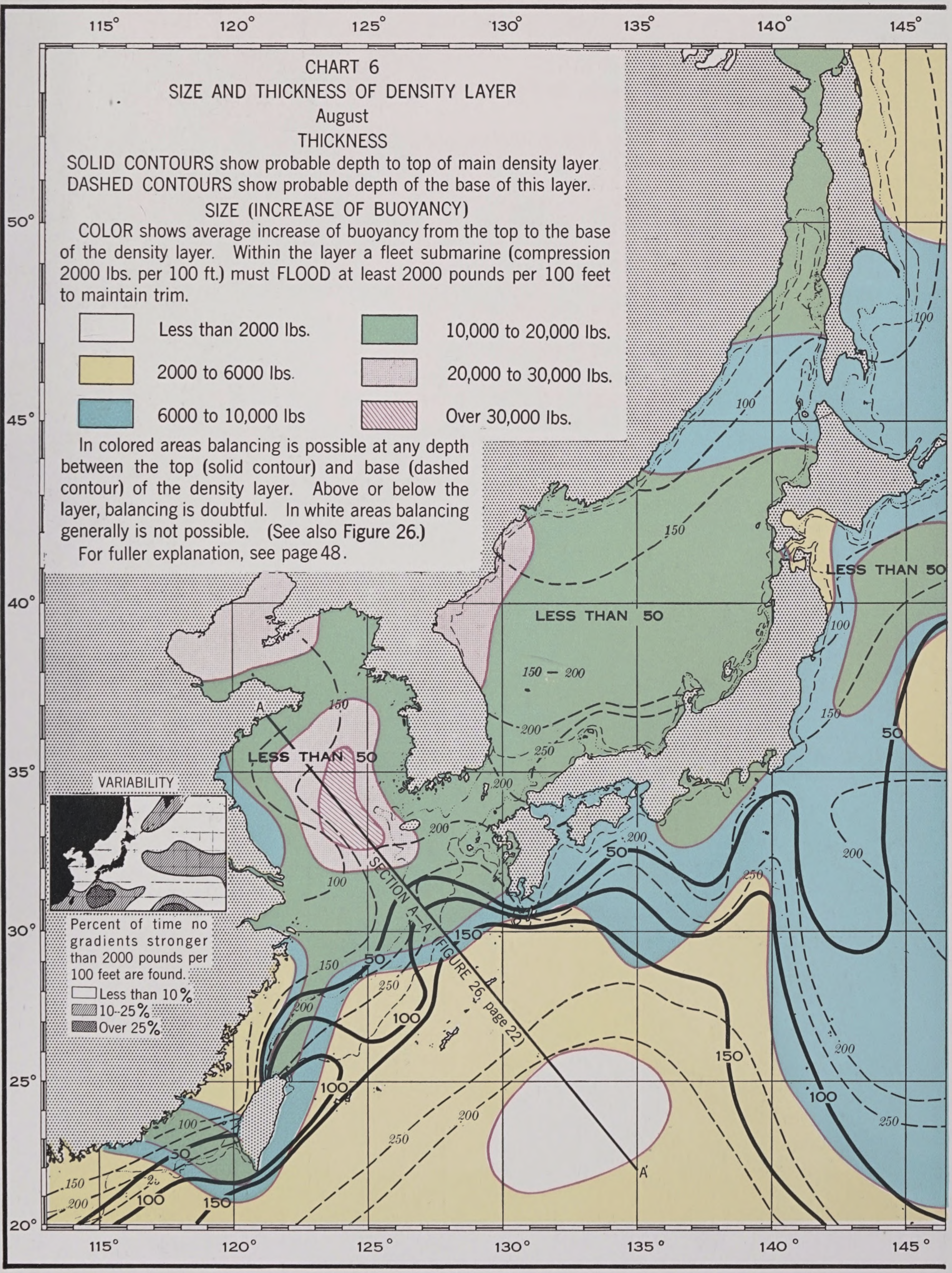


FIGURE 7. A part of Chart 6 from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating size and thickness of the density layer.

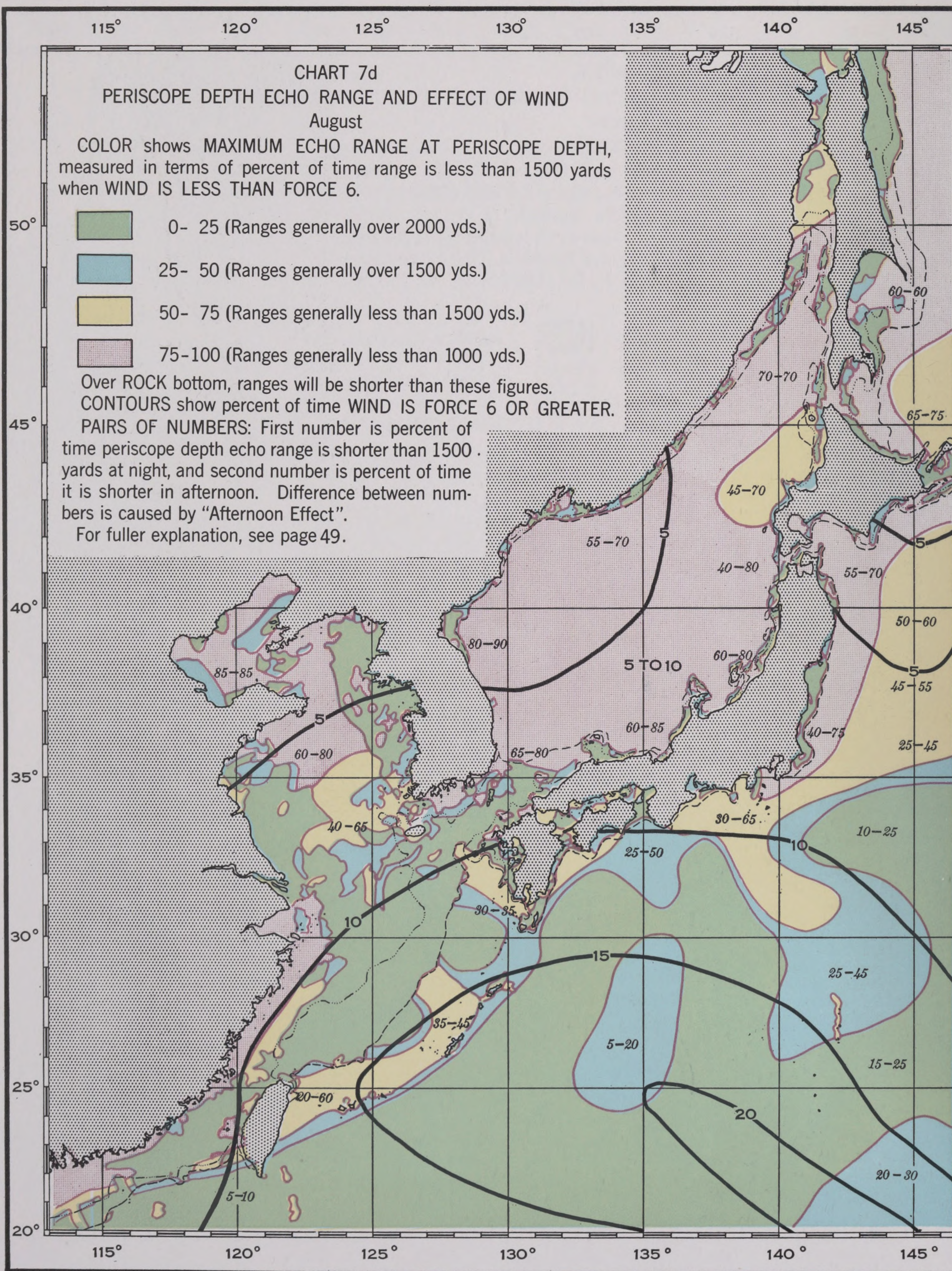


FIGURE 8. A part of Chart 7d from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating periscope depth echo range and effect of wind.

[redacted]

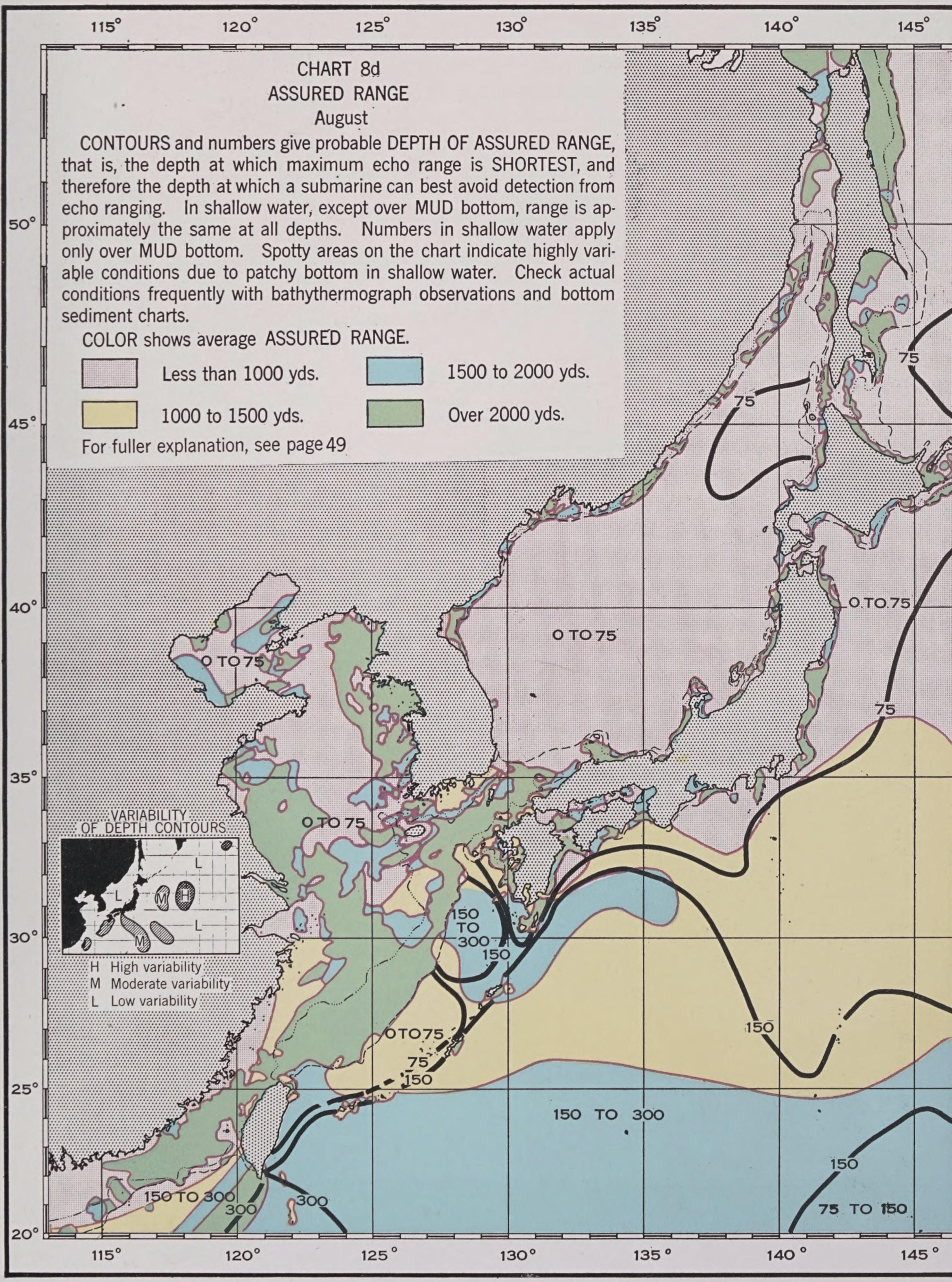


FIGURE 9. A part of Chart 8d from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating assured range.

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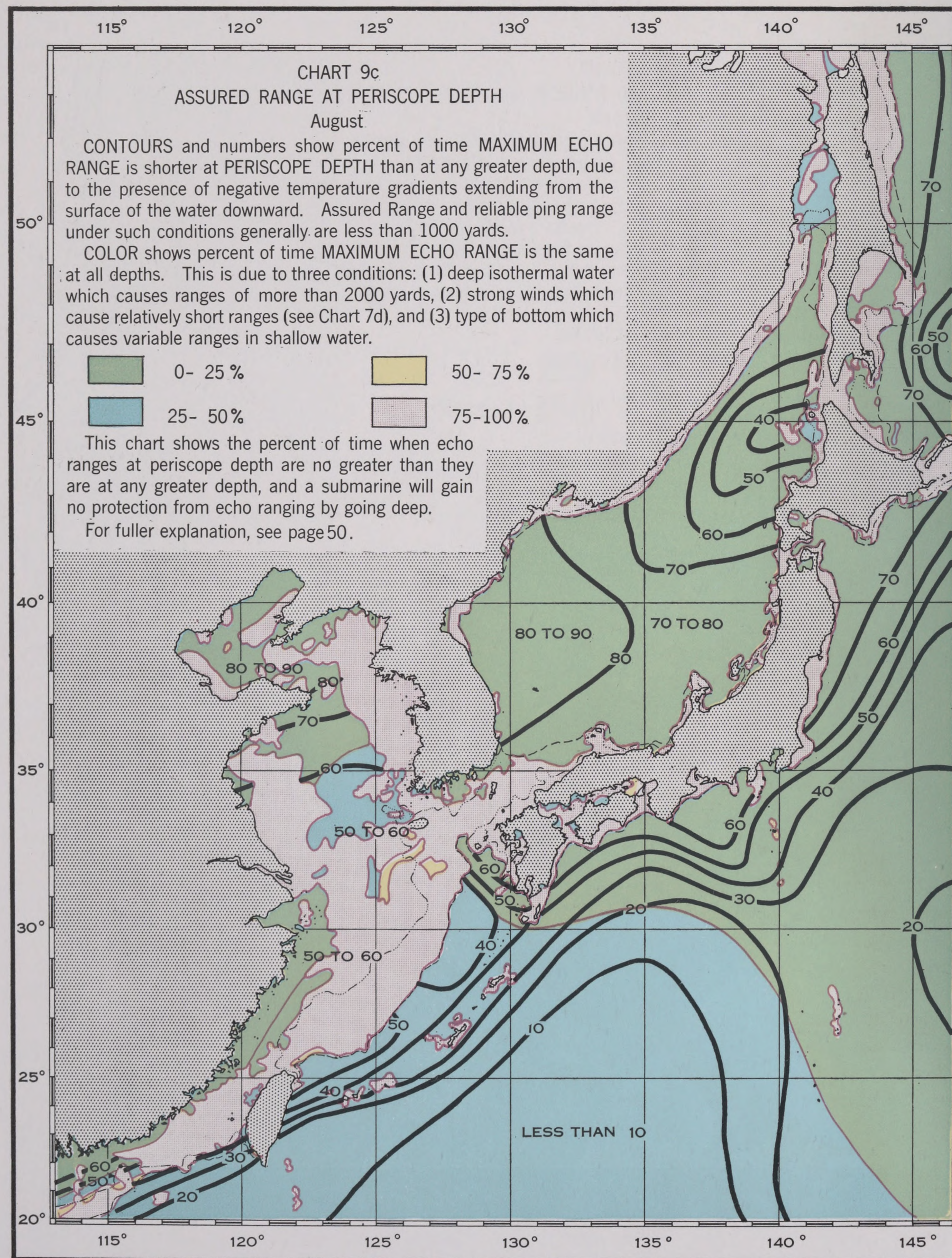


FIGURE 10. A part of Chart 9c from the Submarine Supplement to the Sailing Directions, Japanese Empire Area, H. O. Pub. No. 231, illustrating assured range at periscope depth.

1,500 yards. They do not apply when the wind force is 6 or more, under which condition shorter ranges are to be expected. Contours also indicate how frequently wind forces of 6 or more are to be expected. The charts thus show the probability that local conditions will favor undetected operations at periscope depth. (See Figure 8.)

Assured Range

These charts show the depth at which maximum echo ranges are probably shortest and the ranges to be expected at that depth. They consequently indicate the depths at which a submarine can best avoid detection by echo ranging and the relative chances of detection when at such depths in the various regions. (See Figure 9.)

Assured Range at Periscope Depth

This chart shows the percentage of time that echo ranges are shorter at periscope depth than at any greater depth. Since unusually poor sound conditions usually accompany this condition the chart indicates the probability that submarines will be at an advantage during aggressive action, both during attack and evasion. (See Figure 10.)

## 11.3 SOURCES OF DATA AND RELIABILITY OF PREDICTIONS

The charts in the supplements were constructed from two types of data:

1. Over 70,000 serial temperature observations from the western Pacific including some salinity observations. These were taken largely by the Japanese and the largest number of the observations are from Japanese waters.
2. Several thousand BT records taken both by American submarines and antisubmarine vessels.

There are some objections to the use of either of these types of data if highly accurate charts are desired. Serial temperatures are usually quite precise but they do not give a complete picture of the subsurface temperature gradients because the temperature is recorded only at a series of separate depths.

Bathythermograph records give a continuous temperature profile, but frequently the temperature is subject to a systematic error of as much as 5 degrees because the recorder is not correctly adjusted. In compiling charts showing the temperature at various depths using BT data, an incorrect result may be obtained. Since temperature differences between the depths in question determine the buoyancy change which will be encountered in diving, these errors do not have a practical effect upon the usefulness of the BT. Similarly BT data may be employed to prepare charts showing the difference in temperature between two depths in spite of the usual errors in adjusting the instrument. A more important objection to the use of BT records secured by Service vessels is that the geographic locations given with the records are often unreliable. This is caused by lack of precision in keeping the data, and is a personnel problem difficult to solve during time of war.

The buoyancy charts in the supplements were constructed largely on the basis of recorded serial temperatures and salinities. There are large areas where the data are scanty, especially that on salinity. Some of the charts contain a small inset to indicate the variability of the data on which they were constructed. In areas where the data had a high variability the average conditions shown are generally less reliable than in areas having low variability.

In the preparation of the charts it was necessary to make the best of the available information and frequently to resort to general oceanographic theory to fill in areas where data was inadequate or even to ignore some data which conflicted with theory. While this was doubtless the most expedient procedure, more useful charts could be constructed if special surveys were made for the purpose in critical areas where general oceanographic information is insufficient. In particular, more detailed information is needed concerning the salinity distribution and concerning the normal variability of the conditions, since these are the two most useful items covered in the supplements.

## Chapter 12

# THE PROBLEM OF RESUBMERGENCE

THE DISCUSSION of the control of buoyancy in the preceding chapters has always started with the assumption that the submarine was in trim at periscope depth or some other depth of submergence. The control of buoyancy on changing depth is simply a matter of adjusting ballast to compensate for the effects which result from compression and from the changing density of the sea water. When a surfaced submarine submerges, difficulty is frequently encountered in bringing the vessel to trim at the desired depth quickly. The submarine may find itself so heavy that it is forced to blow ballast from the safety tank to avoid sinking or it may be so light that it cannot get down until it has flooded additional water into the auxiliary tanks. Neither condition is compatible with efficient operation.

The difficulty arises from two sources. There is no exact method of judging the change in weight of a submarine due to consumption of fuel, stores, and ammunition while it is on the surface; also, there is no convenient means of measuring in advance the buoyancy of the water which will surround the submarine when it reaches the desired depth of submergence.

Careful estimates are made of the changes in weight which occur while submarines are on the surface. If the surface run is not too long these estimates are sufficiently precise to permit compensation to be made before submerging. If longer runs are made on the surface, or if the submarine has docked and taken on supplies, larger errors may arise. For this reason submarines commonly make a dive to establish trim soon after leaving port, and repeat the procedure at least daily while cruising or on patrol.

### 12.1 THEORY OF RESUBMERGENCE

The difficulties which arise as the result of hydrographic factors may best be discussed after considering the general theory of resubmergence.

Let $W_1$ = weight of submarine exclusive of main ballast water.

$w$ = weight of main ballast water.

$V$ = displacement of submarine.

$v$ = displacement of main ballast water.

$\rho^a$ = density of water surrounding submarine at periscope depth at point A, where original trim obtains.

$\rho^b$ = density of water surrounding submarine at periscope depth at point B, where trim is desired on resubmergence.

$\rho^{a/w}$ = density of water in main ballast tanks at point A.

$\rho^{b/w}$ = density of water in main ballast tanks at point B.

It is desired to find $\triangle W$, the change in ballast required to establish trim at periscope depth at point B.

At point A where trim obtained at periscope depth before surfacing:

$$W_1 + v\rho^{a/w} = V\rho^a. \tag{1}$$

At point B after submerging to periscope depth, good trim will obtain when:

$$\triangle W + W_1 + v\rho^{b/w} = V\rho^b. \tag{2}$$

Subtracting (1) from (2):

$$\triangle W = V(\rho^b - \rho^a) - v(\rho^{b/w} - \rho^{a/w}). \tag{3}$$

The ballast adjustment required to compensate for the change in density of the water between the point of surfacing and resubmergence depends upon the change in density of the water at periscope depth and the difference in density of the water in the main ballast tanks before surfacing and after resubmergence. The practicability of applying the relation shown in equation (3) depends on the kind of hydrographic conditions which may be encountered.

### 12.2 RESUBMERGENCE WHEN VERTICAL DENSITY GRADIENTS ARE SMALL

When density gradients present between the surface and periscope depth at both the point of surfacing and resubmergence are small or absent, the density of water in the ballast tanks will be practically the same as that surrounding the vessel, and equation (3) may be written:

$$\triangle W = (V - v)(\rho^b - \rho^a). \tag{4}$$

Furthermore, measurement of the density of the surface water may be used as the value of $\rho^b$, the density at periscope depth at the point of submergence. The surface density at the point of surfacing may also be substituted for $\rho^a$, the density at periscope depth, though this value can be measured from the submerged submarine.

When these simplifications are permissible, the following formula may be used in compensating for changes in the density of the water encountered by a submarine of 2,400 tons submerged displacement while cruising on the surface.

$$\triangle W = 4 \times 10^6 \triangle \rho .$$

This formula assumes that the ballast water displaces one-fourth the displacement of the submerged submarine. It means that 4,000 pounds of ballast should be flooded for each increase in density of 0.001.

When the absence of density gradients near the surface permits the use of the foregoing rule, it may be useful to determine the density of the water with a hydrometer, especially when the horizontal density change is large. A submarine has reported that in passing through the Panama Canal, where the difference in density on the two sides is about 0.002, the hydrometer predicted exactly the compensation required for resubmergence. A submarine equipped with the CXJC buoyancy recorder has found the indications of this instrument helpful in compensating for the difference in density between Long Island Sound, where trim dives were made, and the more saline water encountered in offshore test areas. On the other hand, observations made in the course of daily trim dives during a cruise from New London to Panama indicated that errors in estimating the weight change of the submarine due to consumption of fuel and stores during a 24-hour run were larger than the corrections for the changing density estimated from hydrometer readings, and consequently no advantage was gained from these corrections.

It is not reliable to estimate the change in density from the temperature of the surface waters, because horizontal density gradients are more likely to result from salinity differences than from temperature.

## 12.3 RESUBMERGENCE WHEN VERTICAL DENSITY GRADIENTS ARE LARGE

If the density of the water changes markedly between the surface and periscope depth, the simplified rule discussed above is not reliable, particularly if the gradient is great at the point of resubmergence. All the terms in equation (3) are significant and should be evaluated to secure a dependable prediction. Unfortunately it is not practical to do this.

The density of the water at periscope depth at the point of surfacing, $\rho^a$, can be measured from the submarine before it surfaces, but there is no convenient way of evaluating $\rho^b$, the density of the water at periscope depth where trim is desired after resubmerging. This could be determined with an instrument such as the surface vessel bathythermograph which could be lowered from the surfaced submarine. It has not seemed desirable to resort to this procedure which would add another item to submarine equipment. The water which will fill the main ballast tanks on resubmergence enters the tanks at a depth of about 15 feet. The density of this water, $\rho^{b/w}$, can be obtained with sufficient accuracy from a suitable water line while the submarine is surfaced. The density of the water which is in the main ballast tanks before surfacing, $\rho^{a/w}$, is more difficult to evaluate. If the submarine has been at periscope depth for some time, and the density gradient is due largely to temperature effects, the water in the main ballast tanks may be assumed to be in thermal equilibrium with the surrounding sea water and its density may be taken as the same as $\rho^a$, the density at a depth of, for example, 55 feet. On the other hand, if the submarine has recently submerged, as will be the case if the usual trim dive is made in the course of a cruise, the water in the main ballast tanks will be similar to that at about 15 feet below the surface.

These uncertainties, particularly the difficulty in determining the density at periscope depth in advance of submerging, make it impossible at present to predict the correct ballast compensations under the very conditions in which difficulty is most likely to be encountered.

Submarines should be particularly cautious when resubmerging in the water of low density which is found along coasts where the surface sea water is diluted with river water. In such situations very strong salinity gradients often occur between the surface and periscope depth. If a submarine, which has surfaced after obtaining trim offshore, enters such an area and attempts to compensate its weight on the basis of measurements of the density of the water near the surface it will be too light when it descends into the denser water beneath the surface. It will be in danger of broaching when the negative tank is blown when leveling off to come to trim. On such an occasion it will be necessary to retain an excess of ballast in the negative tank until a compensating amount of ballast is flooded into auxiliaries.

The following rules have been developed to guide a submarine which is in trim and measures the density of the water at periscope depth at the point of surfacing and again determines its density at a depth of about 15 feet at the point where it expects to resubmerge.

1. When the density at 15 feet is greater than the density at periscope depth at the previous point of surfacing, the submarine will be light if it dives unless additional ballast is flooded. It is advisable to run with the boat heavy.

2. When the density at 15 feet is the same as the density at periscope depth at the previous point of surfacing, the submarine may be light or in trim if it dives. It may be advisable to run with the boat heavy.

3. When the density at 15 feet is less than the density at periscope depth at the previous point of surfacing, diving conditions are unpredictable. Where there is a strong temperature or salinity gradient at shallow depths, difficulty may be encountered on submergence. Since conditions cannot be predicted at periscope depth it may be advisable to go down on the planes at high speed, and to make ballast adjustments according to the feel of the boat after greater depths are reached.

## 12.4 SUBMARINE SUPPLEMENTS AS AN AID IN RESUBMERGENCE

It might be thought that the Submarine Supplements to the Sailing Directions could give useful information on the density gradients existing between the surface and periscope depth and that this information could be used in estimating the ballast adjustments required for resubmergence. Unfortunately in the situations where these strong gradients occur, the conditions are likely to be very variable. Quantitative information consequently cannot be given. For example, a study of the problems of resubmergence in the Yellow Sea, made by the Scripps Institution of Oceanography, has shown that for resubmerging after a run between two stations 10 miles apart, the ballast compensation estimated according to equation (3) was as follows:

| | | |
|---|---|---|
| August 11, 1932 | Flood | 1,500 pounds |
| August 9, 1933 | Flood | 16,000 pounds |
| August 1, 1934 | Flood | 750 pounds |
| August 17-18, 1935 | Pump | 3,875 pounds |

This variability makes it impossible to furnish submarines with quantitative predictions for resubmergence conditions in such areas as the Yellow Sea.

The earlier editions of the submarine supplements contained maps showing the horizontal distribution of density in the sea's surface, which were intended to indicate whether important changes in buoyancy would be encountered following a surface run. These charts have been omitted from later editions because it appeared that such changes did not occur in large areas of the ocean and because of the difficulty in taking account in a quantitative way of the effects of the vertical density gradients. Since submarines cannot secure the needed information for themselves it is important that the supplements continue to supply the best advice possible for resubmergence. It should at least be possible to show:

1. The areas and seasons where no compensation is required for horizontal changes in density.

2. The areas and seasons where compensation may be made on the basis of measurements of surface density because of the absence of vertical density gradients.

3. The areas and seasons where strong vertical density gradients are likely to create difficulty in resubmergence.

# GLOSSARY

BALANCING. Allowing a stationary submarine to float in a density layer.

BOURDON TUBE. A flattened curved tube which tends to straighten out under internal pressure, used as the driving element in pressure and temperature gauges.

BT. Bathythermograph.

BUOYANCY. As used in this volume, the net buoyancy, or the difference between the weight of the water displaced by a vessel and the weight of the vessel.

COMPRESSION. A coefficient expressing, in pounds per hundred feet, the combined effect on submarine buoyancy of the compressions of sea water and of the vessel with increasing depth. It is always negative in value.

DENSITY GRADIENT. Change in density with depth.

DENSITY LAYER. A layer of water in which density increases with depth enough to increase the buoyancy of a submarine. (Submariner's term for a density gradient.)

ISOBALLAST LINES. A set of lines, on the SBT chart, starting from a set of selected points on the temperature scale and passing through all points for which the net change in buoyancy, resulting from changes in water temperature and depth, is zero for a submarine of a given compression.

SALINITY. Number of grams of salt per thousand grams of sea water, usually expressed in parts per thousand.

SALINITY GRADIENT. Change in salinity with depth, expressed in parts per thousand per foot.

SBT. Submarine bathythermograph.

STABILITY. The resistance to overturn or mixing of the water column, resulting from the presence of a density gradient.

STOP TRIM. The condition of trim, when net buoyancy is zero, whereby a stationary submarine can maintain its depth.

TEMPERATURE GRADIENT. Change of temperature with depth, expressed in degrees F per foot.

THERMOCLINE. A layer of water in which temperature decreases with depth; a negative temperature gradient.

TRIM. The adjustment of submarine buoyancy.

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| NS-140 Ext. | Acoustic properties of the sea bottom |
| NS-140 | Range as function of oceanographic factors |
| NS-308 | Sonar-surface and submarine Bathythermograph instruction program |

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